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Left-hemispheric Specialization In Normal Subjects For Judgments Of Successive Order And Duration Of Nonverbal Stimuli

Frances Laurain Mills

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LEFT-HEMISPHERIC SPECIALIZATION IN NORMAL SUBJECTS FOR JUDGMENTS OF SUCCESSIVE ORDER AND DURATION OF NONVERBAL STIMULI

by

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Submitted in partial fulfillment
of the requirements for the degree of
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the vocal tract, called formants, are rapidly shifted in frequency as the tract changes shape during the production of a consonant-vowel pair. The specific patterns of shift of the formant locations in the voice spectrum, called the formant transitions, have been shown to be an important cue in the perception of consonants (Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1962). The formant transitions are associated with stop consonants, semivowels and laterals, but not with steady-state vowels. Darwin (1971) reports a study using synthetic speech in which the formant transition component of fricative speech sounds was present or deleted from the sound. In dichotic presentation, he found that sounds containing formant transitions yielded a right-ear advantage whereas sounds with deleted transitions did not.

Thus, while dimensions of vocality or conceptual content do not appear to provide a basis underlying the lateralization in the left hemisphere of a verbal stimulus for dichotic perceptual experiments, the presence or absence of a formant transition may. The lateralized processing shown for speech sounds containing formant transitions may result from the fact that the formant transition is primarily a temporal cue, varying in rate of change and in duration (20 to 80 msec). The presence of such temporal cues may be at least one of the critical characteristics of verbal stimuli underlying their processing in the left hemisphere. Linguistic analysis of speech shows the importance of temporal patterning at several

ABSTRACT

A series of experiments examined the role of the left cerebral hemisphere of normal subjects for the discrimination of temporal features of nonverbal, auditory stimuli. Specifically, subjects were presented with tasks requiring: 1) identification of the temporal order of two stimuli, each presented to a different ear; 2) a reaction-time response to the offset of monaural pulse sequences varying in presentation rate; 3) discrimination of small differences in duration for either ear in a delayed-comparison task. In each task, an advantage for the right ear was observed suggesting that the left hemisphere may be specialized for the discrimination of temporal patterns. Furthermore, a right-ear advantage in the reaction-time task was shown for rates having an interpulse duration of 40 msec and 50 msec but not for rates with an interpulse duration of 67 msec or 100 msec. These data were interpreted to reflect selective left hemisphere involvement in analysis of temporal patterns dependent upon a critical order of magnitude of temporal cues within the pattern. The findings are discussed in terms of possible timing mechanisms localized in the left hemisphere. Specifically, it is hypothesized that the left hemisphere contains a timing mechanism specialized for the analysis of temporal cues within phonemes and that this mechanism is also involved in the resolution of similar small durations present in nonverbal stimuli.

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CHAPTER I

INTRODUCTION

In 1861, the left cerebral hemisphere in humans was identified as serving a primary role in the processing of speech. This conclusion was first reached through clinical observations of brain-damaged patients (Broca, 1861; cited in Penfield & Roberts, 1959) and has repeatedly received confirmation from investigations of both brain damaged (reviewed in Penfield & Roberts, 1959) and normal subjects (reviewed in Kimura, 1968; Milner, 1971).

To provide an account of left hemisphere lateralization of speech function, investigators have attempted to determine more elementary left hemisphere processes upon which the perception and production of speech may be based. Kimura (1976) has demonstrated that aphasics are impaired in performance of complex nonverbal motor movements of the upper limbs and suggests that left hemisphere mechanisms involved in speech production are functionally related to those involved in producing complex muscular movements. Efron (1963b) has adopted a similar reductionist approach. Having demonstrated that aphasics are impaired in judging the order of occurrence of nonverbal stimuli, he suggests that aphasia is primarily a temporal disorder. Consequently, he has speculated that the left hemisphere contains

specialized timing mechanisms which presumably regulate both perception and production of speech sounds.

In the present investigation an attempt was made to examine the generality of the notion that the left hemisphere may be specialized for the temporal analysis of verbal and nonverbal stimulation. Accordingly, hemispheric asymmetry for processing nonverbal stimuli within a variety of temporal tasks was assessed. In addition, an attempt was made to examine possible constraints on the generalization that temporal analysis of stimulation is subserved by the left hemisphere. If, as Efron (1963b) has suggested, it is the temporal structure of speech which provides the basis for its lateralization in the left hemisphere, then it seems possible that in nonverbal temporal tasks, only stimuli with temporal properties comparable to those of speech will produce a hemispheric asymmetry.

To further develop the rationale for the present research, literature pertaining to the left hemisphere's involvement in speech processing will be selectively reviewed and discussed.

Localization of Language within the Left Hemisphere

The lateralization of language processes within the left hemisphere has been summarized in terms of a verbal - nonverbal dichotomy (Milner, 1962). Clearly, such a dichotomy is of limited value unless the features or properties characterizing a stimulus or a task as verbal

can be specified. The term "verbal" has been defined as "concerned with words" (Concise Oxford Dictionary, 1964) and yet, not all stimuli "concerned with words" are processed within the left hemisphere. The specific demands of the experimental task influence the pattern of lateralization observed (Darwin, 1971; Moscovitch, 1976; Shankweiler & Studdert-Kennedy, 1970; Spellacy & Blumstein, 1970). To fully account for the lateralization of functionally verbal stimuli, it is necessary to determine those properties of the stimulus which promote left hemisphere processing.

There are several features of stimuli which might identify them as verbal but which do not appear critical to left hemisphere specialization. For example, auditory verbal stimuli are produced within the vocal tract. Yet, the dimension of vocality appears insufficient to selectively trigger left hemisphere mechanisms. King and Kimura (1972) have reported that sounds such as laughing or crying, although produced in the vocal tract, are not primarily processed within the left hemisphere.

A second possible dimension of verbal stimuli which may be critical in primarily engaging left hemisphere mechanisms is conceptual content. Several studies with normal subjects have indicated that words, nonsense syllables, consonant-vowel bigrams, and digits, although varying widely in their degree of conceptual content, need not vary in the degree to which they appear lateralized for processing in the left hemisphere (for summary of

scores, see Harshman & Krashen, 1974).

On the other hand, not all stimuli which appear verbal in nature are processed principally in the left hemisphere. Dichotic listening studies have revealed that isolated steady-state vowels approximating 200 msec are an exception to the typical lateralization pattern for verbal stimuli. Though stop consonants (/p/, /b/), semivowels (/w/, /v/), and laterals (/l/, /r/) appear primarily processed in the left hemisphere, steady-state vowels (/o/, /a/) are not (Haggard, 1971; Studdert-Kennedy & Shankweiler, 1970). It is to be noted that when vowels are shortened and/or degraded by a background of white noise, they may be lateralized to the left hemisphere (Godfrey, 1974; Studdert-Kennedy, 1973; Weiss & House, 1970); although there is conflicting data with respect to the lateralization pattern of simply shortened vowels (Darwin, 1969). The implications of these instances of vowel lateralization to the left hemisphere will be considered in the general discussion. For the present argument, a possible basis for the different lateralization pattern of consonants compared to non-degraded steady-state vowels is the relevant issue. One explanation offered for these differences is that verbal stimuli must contain rapid frequency changes in order to be processed in the left hemisphere. The type of rapid spectral energy changes important for phonemic distinctions are produced as the articulators move from the position of a consonant to a vowel. The characteristic resonances of

the vocal tract, called formants, are rapidly shifted in frequency as the tract changes shape during the production of a consonant-vowel pair. The specific patterns of shift of the formant locations in the voice spectrum, called the formant transitions, have been shown to be an important cue in the perception of consonants (Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1962). The formant transitions are associated with stop consonants, semivowels and laterals, but not with steady-state vowels. Darwin (1971) reports a study using synthetic speech in which the formant transition component of fricative speech sounds was present or deleted from the sound. In dichotic presentation, he found that sounds containing formant transitions yielded a right-ear advantage whereas sounds with deleted transitions did not.

Thus, while dimensions of vocality or conceptual content do not appear to provide a basis underlying the lateralization in the left hemisphere of a verbal stimulus for dichotic perceptual experiments, the presence or absence of a formant transition may. The lateralized processing shown for speech sounds containing formant transitions may result from the fact that the formant transition is primarily a temporal cue, varying in rate of change and in duration (20 to 80 msec). The presence of such temporal cues may be at least one of the critical characteristics of verbal stimuli underlying their processing in the left hemisphere. Linguistic analysis of speech shows the importance of temporal patterning at several

different levels of observation, beginning with formant transitions within the phoneme and extending to the order of sounds within a word, and of word and sentence structure, including the appropriate pauses between these elements (Hirsh, 1967).

On the basis of this type of argument, Efron (1963b) has suggested that the superiority of the left hemisphere for the processing of verbal material may reflect a specialization for temporal analysis of speech sounds. In particular, he has suggested that language is represented in the left hemisphere because a "specialized time-labelling mechanism" exists there. According to this hypothesis, information concerning the time of occurrence of two events, whether speech or nonspeech, is processed primarily in the left hemisphere.

Localization of Function for Temporal Discrimination of Nonverbal Stimuli

A number of investigations have reported data indicating a specialization of the left hemisphere for temporal processing of nonverbal events. Efron (1963b) studied the ability to judge the correct temporal order of two successive visual or auditory stimuli. He observed that aphasic patients, suffering left-hemisphere damage, required a greater temporal separation between successive stimuli to accurately assess their order. That is, aphasics had higher temporal-order thresholds than did nonaphasic

brain-damaged patients. Specifically, the nonaphasic patients were able to judge the order of stimulus presentation with 100 per cent accuracy when the stimuli were in the range of 75 to 150 msec in the visual and 62.5 to 162.5 msec in the auditory modality. The corresponding threshold values obtained with aphasic patients ranged from 112.5 to 350 msec for the visual and from 162.5 to 700 msec for the auditory modality.

In a similar study of normal subjects, brain-damaged nonaphasic patients, and left-hemisphere-damaged aphasic patients, Edwards and Auger (1965) obtained auditory temporal-order thresholds of approximately 67 msec, 50 msec, and 141 msec for the respective groups. Finally, Swisher & Hirsh (1972) employing successive visual and auditory stimulation obtained temporal-order thresholds in the range of 9 to 40 msec for normal subjects, 26 to 100 msec for right-brain-damaged nonaphasic patients, and 36 to beyond 320 msec for left-hemisphere-damaged aphasic patients.

The results of these studies as well as closely related findings with sequences of three to five stimuli, to be discussed below, indicate that damage to the speech areas of the left hemisphere disrupted the ability to make temporal discriminations. For this reason, the authors have suggested that the language deficit observed in aphasics may reflect a more general sequencing defect, producing an inability to input and time-label stimulation at normal rates of presentation.

The concept of a general sequencing mechanism situated within the left hemisphere has received support from a study of normal subjects (Efron, 1963a). The subjects were presented with pairs of successive light flashes in which one member of each pair was delivered to the left visual field and the other member of the pair was delivered to the right visual field. The temporal interval separating the successive light flashes was reduced over trials until the subjects were no longer able to correctly report the order of occurrence and instead reported that the stimuli had occurred simultaneously. Efron found a larger threshold for report of simultaneity in the condition in which the left-field stimulus preceded the right-field stimulus, than in the condition where the reverse order was presented. The difference between the left-first threshold and the right-first threshold was approximately 4 msec and was statistically significant.

Efron (1963a) accounted for this finding by assuming that the comparison of temporal order and the subsequent decision of simultaneity occurred within the left hemisphere. Since the left-field stimulus was initially directed to the right hemisphere, information concerning it required more time to reach the left hemisphere than was required for the right-field stimulus. Thus, the higher temporal-order threshold obtained for the left-first condition includes this additional transmission time reflecting transfer from the right to the left hemisphere.

These results were also found in the cutaneous modality. Efron (1963a) delivered skin shocks to a finger of the left and right hand under similar conditions and found a higher threshold of apparent simultaneity when the left-finger shock was presented first.

The data reported thus far have indicated that the left hemisphere is predominant in processing the temporal order of two stimuli. It also appears to be specialized in processing temporal sequences containing more than two stimuli.

Carmon and Nachshon (1971) reported a study in which the performance of patients with unilateral left-hemisphere damage, unilateral right-hemisphere damage or no brain damage was compared. The patients were presented with continuous audio-visual sequences containing three, four, or five stimuli. During the presentation of each sequence, the patients were requested to identify the temporal position of each stimulus element in the sequence by pointing. The duration of the stimulus elements comprising a sequence was increased from an initial value of 100 msec to that value enabling 100 per cent correct temporal ordering. The results indicated that nonbrain-damaged control subjects required mean stimulus durations of 250 msec for 3-stimulus sequences and mean stimulus durations of 310 msec for 5-stimulus sequences before attaining a level of 100 per cent accuracy. The right-hemisphere-damaged patients did not differ significantly from the controls, requiring mean stimulus

durations of 220 msec and 400 msec for the 3-stimulus and 5-stimulus sequences. The left-hemisphere-damaged patients, however, differed markedly from both control and right-hemisphere-damaged patients requiring mean stimulus durations of 540 msec for 3-stimulus and 800 msec for 5-stimulus sequences before reaching criterion performance. It is important to note that none of the left-hemisphere-damaged patients employed in this study were observed to be aphasic yet they demonstrated a considerable deficit in perception of temporal order.

Carmon and Nachshon (1971) also reported the mean stimulus durations required by nonbrain-damaged controls, and left and right-hemisphere-damaged subjects for 100 per cent accuracy in identifying the temporal order of elements within a 3-stimulus sequence of visual stimuli alone. Similar results were obtained. Though the left-hemisphere patients required shorter stimulus durations than in the auditory task, their performance was impaired relative to that of the other groups.

In a related study, Albert (1972) examined the ability of right-hemisphere-damaged, left-hemisphere-damaged and nonbrain-damaged patients to accurately assess the order of auditory or visual stimulus sequences. In the auditory task, the experimenter named a series of objects and when the list was complete, requested the patients to point to the objects in the order they had been presented. The visual task was analogous. The experimenter pointed to a

series of objects and, upon completing a given sequence, required the patients to point at the objects in the order they had been presented. Scores were assigned on the basis of the number of correctly ordered objects recalled. The results indicated that both right-hemisphere-damaged and left-hemisphere-damaged patients obtained lower performance scores on the auditory task than did the nonbrain-damaged groups. Moreover, aphasic left-hemisphere-damaged patients demonstrated a significant impairment on the auditory task relative to both right-hemisphere and nonaphasic, left-hemisphere-damaged patients. However, no significant differences in performance were obtained on the visual analogue of this task.

Mateer and Kimura (1976) have also reported that aphasic patients show no greater impairment than nonaphasic, brain-damaged patients in a task requiring temporal sequencing of visual material. Aphasic and nonaphasic patients were presented with a card showing a series of geometric designs and then asked to reproduce the series by hand-ordering cards each of which portrayed one design. The results indicated that the performance of aphasic and nonaphasic patients did not differ significantly.

Although Carmon and Nachshon (1971) reported that patients with left-hemisphere damage demonstrated an impairment in correctly ordering three visually presented stimuli, and other studies (Edwards & Auger, 1965; Efron, 1963b; Swisher & Hirsh, 1972) have reported similar impairment when left-damaged patients were required to identify

the order of two visually presented stimuli, neither Albert (1972) nor Mateer and Kimura (1976) reported such a result. The apparent discrepancy of these findings may be partially attributable to the differences in stimulus presentation rate employed across studies. Albert (1972) and Mateer and Kimura (1976) presented the visual stimuli manually at a rate which, though unspecified, would necessarily be less than one stimulus per second. In the Carmon and Nachshon (1971), Edwards and Auger (1965), Efron (1963b) and Swisher and Hirsh (1972) studies stimuli were separated by less than 500 msec. It appears, therefore, that left-hemisphere damage may impair temporal sequencing, at least for visual tasks, only if the separation between stimuli is less than some critical value. Above this critical value, both hemispheres may be equivalent in their ability to provide temporal analysis of nonverbal stimulation.

Studies of normal subjects lend support for the finding that rapidly occurring temporal patterns are necessary to observe left-hemisphere specialization for processing. Halperin, Nachshon and Carmon (1973) dichotically presented sequences of three tones which varied in their degree of complexity. Complexity was defined by the number of transitions of short (200 msec) and long (400 msec) tones within the sequence. The intertone interval was always 200 msec. They found a left-ear advantage for report of tone order of sequences without transitions and a right-ear advantage for similar report of sequences containing

one and two transitions. They interpreted this finding as reflecting a superiority for processing temporal characteristics of auditory patterns.

In a similar study (Papcun, Krashen, Terbeek, Remington, & Harshman, 1974), Morse code signals were dichotically presented to Morse code operators and naive subjects. The duration of a unit within the pattern varied for each group of subjects; the shortest unit was 45 msec and the longest unit was 101.3 msec. One unit represented a dot or a space whereas three units represented a dash. The total number of units presented in a signal was 13. (However, the naive subjects were also tested with 6-unit signals.) The operators were required to type the signals they heard in corresponding alphabet letters and the naive subjects were required to write the signals in dot and dash form. Report for the right-ear signals was found to be more accurate than report for the left-ear signals for Morse code operators. The naive subjects showed superior identification for right ear signals of six units but not for the longer signals of 13 units. In this case, the left ear was more accurate.

In general, the results from both studies of normal subjects are consistent with the data obtained from brain-damaged patients. The left hemisphere is superior to the right in processing temporally patterned nonverbal stimuli. Moreover, this superiority was evident in the discrimination of rapidly occurring temporal patterns since the longest

stimulus within any pattern was 400 msec.

Memory for stimulus duration is another kind of temporal discrimination investigated in brain-damaged subjects. A study reported by van Allen, Benton and Gordon (1966) investigated the discrimination of duration in patients with left or right-brain damage, bilateral brain damage and in control subjects without brain damage. Stimulus pairs of two sounds, two lights, or a sound and a light were successively presented and the subject was asked to identify the longer stimulus within the pair. A standard duration of 700 msec was used; comparison durations were 400, 500, 600, 800, 900, and 1000 msec. The length of the interstimulus interval was either 1.5 sec or 12 sec. At the 1.5 sec interstimulus interval, the mean performance of the brain-damaged patients was poorer than the controls for each comparison. Differences observed between brain-damaged groups were not significant by statistical test, although a higher error score was shown for patients with left-hemisphere lesions. At the 12 sec interstimulus interval, discrimination was slightly facilitated for the brain-damaged groups compared to their performance at the 1.5 sec interstimulus interval. There was no facilitation shown for the control group at the longer interstimulus interval although their performance was still superior to that of the brain-damaged groups.

Gordon (1967) partially replicated this study in the auditory modality and her findings are similar. The number

of errors in discriminating a difference between two durations was higher in a group with lesions of the left hemisphere compared to a group having lesions of the right hemisphere.

Both of these studies reported duration discrimination deficits in brain-damaged subjects without aphasia. However, differences in impairment as a function of the side of damage were significant only as observed in Gordon's study but not in van Allen et al's study. The discrepancy between the results of these studies may partially result from the lack of aphasic impairment in the subjects. A comparable task (Needham & Black, 1970) was presented to aphasic and nonbrain-damaged subjects and significant differences were reported. The aphasics required a larger difference in duration between the tones for correct judgments and showed a higher difference threshold (86 msec) than found for nonaphasic subjects (40 msec).

An evaluation of the group of studies investigating temporal discriminations indicates that the relation of aphasia to temporal impairment is unclear. The presence of aphasia is not a necessary condition for demonstration of temporal impairment following left hemisphere damage; as observed in the perception of audio-visual sequences (Carmon & Nachshon, 1971) and duration judgments (Gordon, 1967). Nevertheless, aphasia is a sufficient condition for demonstration of temporal impairment since aphasics were consistently impaired in perception of the successive order of two stimuli (Edwards & Auger, 1965; Efron, 1963b;

Swisher & Hirsh, 1972), in perception of sequences containing more than two stimuli (Albert, 1972), and in comparison of stimulus duration (Needham & Black, 1970).

It is possible that persons with damage to the left hemisphere which, however, did not produce aphasia would be impaired in language related processes not necessarily associated with the occurrence of aphasia. For example, the nonaphasics in Gordon's (1967) study who showed impairment for memory of duration following left hemisphere damage obtained a lower verbal intelligence score than the right-damaged group. Thus, it is reasonable to infer that damage to the left hemisphere may interfere with language processes even in the absence of an observed aphasia.

Present Investigation

Previous studies have indicated that the left hemisphere may be specialized for processing temporal information. However, the majority of these studies have been conducted with brain-damaged subjects. Given that brain damage *per se* may be accompanied by general as well as specific impairment of functioning, the conclusions drawn from studies of brain-damaged patients may not be representative of the normal brain. Moreover, the few existing studies of normal subjects have employed a restricted range of tasks and stimuli. At present, a left-hemisphere specialization for processing temporal information in normal subjects has been reported for tasks requiring the

report of tonal sequences (Halperin et al, 1973; Papcun et al., 1974), and for tasks requiring the perception of simultaneity in the visual and cutaneous modalities (Efron, 1963a).

One goal of the present investigation was to examine the generality of the hypothesis that the left hemisphere is specialized for temporal processing. Accordingly, temporal processing of auditory stimuli was examined using normal subjects within a number of tasks not previously employed with normal subjects. In Experiment I, subjects were required to judge the successive order or simultaneity of two stimuli. Though Efron employed a similar procedure with normals, his observations were limited to visual and cutaneous stimuli, and Hirsh and Sherrick's (1961) study of auditory temporal order did not include an analysis of ear asymmetries (see page 23). Experiments II, III, and IV examined possible hemispheric specialization for processing stimulus duration, a task which has received limited study, and that only with brain-damaged subjects. Two procedures were involved. Experiments III and IV employed a delayed-comparison task similar to that previously used only with brain-damaged subjects, and Experiment II employed a reaction time task which has not previously been examined either with brain-damaged or with normal subjects.

A second goal of the present research was to clarify the possible relationship between left-hemispheric specialization for processing temporal information, and left-hemispheric specialization for processing speech. The theoretical account of left-hemispheric temporal specialization

is based largely on the known superiority of the left hemisphere for processing speech, plus the fact that temporal cues are one important characteristic of speech. However, while a relationship has been suggested between the left hemisphere's temporal and speech functions, it has not received further specification. If such a relationship exists, it is conceivable that temporal discriminations for nonverbal auditory stimuli would involve left-hemisphere mechanisms if the stimuli possessed temporal units approximating the order of magnitude of those composing particular aspects of the temporal structure of speech. This structure may be described with reference to temporal parameters associated with correct perception of phonemes, of syllables and of larger units such as phrases and sentences. The stimulus values chosen for the duration tasks of the present study were based on the phoneme, permitting a comparison of nonverbal temporal discriminations with temporal discriminations underlying phonemic distinctions.

Methodology for demonstrating asymmetry in normal subjects

The use of normal subjects requires techniques which enable the investigator to sample as selectively as possible left or right hemisphere function. In the auditory modality, this may be accomplished through both dichotic and monaural stimulation.

Dichotic stimulation involves the simultaneous presentation of two different sounds to a subject; one sound is directed exclusively to the right ear while the

other is directed to the left ear. While neural connections may be traced from each ear to both cerebral hemispheres, there is evidence that the contralateral ear-hemisphere connections have functional priority over the ipsilateral ear-hemisphere connections. This evidence is based on electrophysiological studies which show a larger cortical response to contralateral stimulation compared with ipsilateral (Rosenzweig, 1951; Tunturi, 1946), a difference which is enhanced during dichotic stimulation (Hall & Goldstein, 1968).

The electrophysiological results are supported by behavioral studies with neurological patients. Lesions of the temporal lobe produce greater hearing loss for distorted speech in the ear contralateral to the lesion (Bocca, Calearo, Cassinari & Migliavacca, 1965; Kimura, 1961) and may also impair perception of short durations in the contralateral ear (Karasseva, 1972). The functional prepotency of the contralateral pathways during dichotic stimulation may be strikingly observed in patients with commissural sections. Milner, Taylor and Sperry (1968) and Sparks and Geschwind (1968) presented split-brain patients with speech sounds using dichotic and monaural presentation. In the dichotic condition, report from the right ear was almost perfect whereas report from the left ear was close to zero. In the monaural condition, the accuracy of report did not differ between the ears. Thus, the competition between inputs created by dichotic presentation appeared sufficient

to effectively suppress the ipsilateral transmission of information.

This anatomical feature of the auditory modality provides a means of assessing the specialization of either hemisphere for the analysis of different stimuli. It is assumed that information arriving directly at the hemisphere specialized for its processing will be more accurately identified than information which is degraded through transcallosal transmission. Since the left hemisphere is specialized for the processing of verbal information, a right-ear advantage in recall of verbal material dichotically presented would be expected. In fact, numerous studies using dichotic stimulation have found a higher accuracy of identification for verbal material reported from the right ear than from the left ear (reviewed in Harshman & Krashen, 1974).

Although dichotic stimulation appears to enhance the functional difference between the contralateral and ipsilateral auditory pathways, an ear difference can also be revealed with monaural stimulation. H. Gordon (1975) reports a study in which verbal stimuli were monaurally presented to patients who suffered surgical disconnection of the hemispheres. The response measured was vocal reaction time for two main conditions; repeating the verbal stimulus when it was heard or monitoring its occurrence by repeating another word. Gordon assumed that the left hemisphere was specialized for performance in both of these verbal tasks,

therefore stimulation of the left or the right ear corresponded to stimulation of the ipsilateral or contralateral pathways respectively. He reported significantly shorter reaction times to right-ear stimulation in the word repetition condition and inconsistent differences in the monitoring condition, although a trend was observed towards shorter reaction times to right-ear stimulation. He concluded that there are differences in the functional strength of ipsilateral and contralateral ear-hemisphere connections even during monaural stimulation, an observation in accord with the electrophysiological data.

A study conducted by Bakker (1969) showed superior recall of letters presented monaurally to the right ear, compared to the left, when the correct serial order was required in the response. If the order was not required, as in the free-recall condition, then an ear advantage was not shown.

A right-ear advantage has also been shown for sentences presented monaurally (Frankfurter & Honeck, 1973), and for identification of monaurally presented consonant-vowel syllables in a task which required a judgment of same or different as compared to a previously heard binaural syllable (Morais & Darwin, 1974).

The demonstration of a right-ear advantage for verbal material following monaural stimulation may depend upon the complexity of the task. In each of the studies reported which showed a right-ear advantage, hemispheric asymmetry in memory may have been assessed. In contrast, a right-ear

advantage in a primarily perceptual task is tenuous. Catlin, Vanderveer and Teicher (1976) found reaction time to be shorter in the right ear compared to the left for the detection of the presence or absence of a consonant-vowel syllable. Using a per cent correct response measure, however, an ear difference was not revealed. These findings suggest that ear differences in monaural tasks of a perceptual nature may require a more sensitive response measure than per cent correct. When the task puts some demand on memory, however, per cent correct appears to be an adequate response measure.

In the present investigation, dichotic tasks were used in Experiments I, II, and III, whereas a monaural task was employed in Experiment IV. Since this task required the use of memory processes, an ear difference would be expected, in accordance with the ear differences shown previously for similar types of monaural tasks.

CHAPTER II

METHOD, RESULTS AND DISCUSSION

EXPERIMENT I

Perception of Temporal Order

The purpose of the present experiment was to replicate and extend to audition Efron's (1963a) results which indicated that the discrimination of rapid temporal order for two stimuli occurred most efficiently within the left cerebral hemisphere. Hirsh and Sherrick (1961) using a comparable paradigm in the auditory modality reported data indicating an ear asymmetry consistent with Efron's (1963a) cutaneous and visual data. However, they do not report on the statistical significance of the differences since the purpose of their study was not to investigate cerebral asymmetry in the perception of temporal order. Also, their procedure differed from that of the present study in that they did not allow judgments of simultaneity. In the present study, subjects were presented with pairs of clicks, one member of the pair to either ear, within a background of binaural white noise. The interval of time separating the paired clicks was varied to include intervals at which their temporal order could be resolved as well as intervals at which the temporal distance between stimuli was too small to allow a discrimination of temporal order. In this case subjects were instructed to call the stimuli "simultaneous", as in Efron's procedure, even

though two distinct stimuli could still be heard and only the order was unclear. The judgment of "simultaneity" indicated that the two stimuli were heard as occurring "together" in time. This judgment necessarily includes the perception of successiveness and thus was termed by Efron the "threshold of apparent simultaneity".

In the auditory modality, the perception of successiveness may occur at values of temporal separation approximating 2 msec (Hirsh, 1959). Although a value of 2 msec temporal separation is sufficient for the discrimination of successiveness Hirsh and Sherrick (1961) have found that a value approximating 20 msec is necessary for the discrimination of temporal order. Furthermore, this value of 20 msec was the same for visual, auditory and tactile stimulation. They concluded that the threshold for the judgment of temporal order depends upon a centrally mediated process whereas the threshold for the judgment of successiveness depends upon a peripheral level of auditory analysis. Subsequent research (Babkoff & Sutton, 1963 ; Efron, 1973; Patterson & Green, 1970) has indicated that correct judgments of temporal order may be obtained at smaller values than those determined by Hirsh and Sherrick (1961) when the stimuli are presented so as to interact close to the periphery of the auditory system. Babkoff and Sutton (1963) showed that two dichotic stimuli presented at equal loudness levels would not be judged equally loud when separated by small intervals (e.g. less than 10 msec but more than 2 msec). At these small separations when the stimuli were perceived to be different in loudness, then the

temporal order judgments were made with better than chance accuracy because the louder stimulus was identified as the leading stimulus. In a series of related experiments, Patterson and Green (1970) and Efron (1973) showed that the temporal order of two auditory stimuli could be resolved when the separation between onsets was in the order of 2 msec. These authors suggested that this discrimination was based on differences in the perceived pitch of the composite sound caused by the order of each stimulus in the pattern.

The studies showing correct perception of order when stimuli are separated by 2 msec suggest that temporal acuity is dependent upon qualitative differences in the sound which result from peripheral interaction of the two stimuli. However, when a separate representation of each stimulus is received by higher centers and an order judgment made, the threshold value approximates 20 msec or more (Hirsh & Sherrick, 1961; Efron, 1963a). The basis for this order judgment would seem to reside in a central mechanism, as suggested by Hirsh and Sherrick, since the temporal separation at which the correct order judgment is obtained is beyond the range associated with peripheral interaction of the stimuli and is the same for all the different sensory modalities tested. Since judgments of temporal order based on independent representations of stimuli are associated with central mechanisms, this type of temporal order task was chosen for the study of hemispheric asymmetry.

The mean interval of time between clicks for a judgment of "simultaneity", called the threshold of temporal order, was computed for right-ear and for left-ear first conditions.

If the left hemisphere is specialized for discrimination of the temporal order of the clicks, it would be expected that the threshold would be smaller in trials where the right ear received the first click (RF) than in trials where the left ear received the first click (LF). The basis for an hypothesized threshold difference between ears based on Efron's (1963a) rationale, derives from differences in strength between the contralateral and ipsilateral pathways of the auditory system (discussed in Chapter I). More time is required for information about the left-ear click to reach the left hemisphere, since it is transmitted first to the right hemisphere on the contralateral pathways, and then sent to the left hemisphere. In comparison, right-ear clicks proceed directly to the left hemisphere by the strong contralateral pathways. Any contribution from the ipsilateral pathways would tend to alleviate this asymmetry but should not cancel or reverse it. Therefore, the larger hypothesized threshold in the left-first condition is based on the measurement of differences in transmission time for the arrival of two clicks at a single location in the brain. (See Appendix A for a schematic portrayal of this rationale.) If the locus of processing for this task were exclusively in the right hemisphere, then by the same rationale a larger threshold value would be expected in the condition where the right-ear click was delivered first. Moreover, bilateral processing should result in equal right and left ear thresholds.

Two psychophysical methods were used to obtain a

threshold measurement; they are described separately in Part A and Part B.

Part A

Subjects

A sample of 10 right-handed college students participated in the experiment in partial fulfilment of requirements for an introductory psychology course. All were within an age range of 18 to 25 years. The Bekesy audiometer was used to determine subjects' pure-tone thresholds for the left and right ear separately. The resulting audiograms showed that no subject had a difference of more than 5 dB between ears for frequencies spanning 750 Hz to 4000 Hz. Handedness was assessed from a questionnaire consisting of six items. The skills represented were those found by Annett (1970) to be actions consistently performed with the preferred hand (See Appendix B.).

Apparatus

The output of a Tektronix waveform generator was used to trigger two Tektronix pulse generators, each of which produced a square wave pulse of 1 msec duration. Each pulse could be delayed relative to the other by means of a pulse delay control on the pulse generator. The calibration of the delay as well as specification of the pulse was accomplished by viewing them on a Hewlett-Packard oscilloscope immediately prior to the experimental session.

Procedure

A pair of successive pulses was presented to subjects, one pulse to each ear, using the method of descending limits

to control the time between onsets. A total of 10 runs was presented in a prearranged random sequence: five with the pulse to the left ear leading and five with the pulse to the right ear leading. The initial separation between pulses in a run varied from 80 to 100 msec with a step size of 5 msec. A background of white noise was superimposed in both ears during presentation of the pulse pairs to facilitate use of crossed auditory pathways. Aitken (1976) measured right and left hand reaction time to monaural tones with and without contralateral noise. He reported that crossed reaction time (right ear - left hand) was significantly longer than uncrossed reaction time (left ear - left hand) in the presence of white noise, but obtained no difference between conditions in the absence of contralateral noise. He concluded that the presence of white noise favored the transmission of stimulus information via contralateral pathways.

The intensity level of the noise was set at a value estimated by the subject to be equal to the pulse which was 70 dB SL. The subject was instructed to report the ear which received the first pulse of the pair in the case of a successive-order judgment, or to report them as "simultaneous" if he was not able to tell which came first. A run was terminated when the subject reported "simultaneity" for two successive trials. A trial was repeated as many times as necessary for the subject to make a judgment. Two practice runs were given to each subject prior to the experimental runs. The headphone position was reversed for one-half of the subjects to control for any asymmetries in the audio

channels.

Because of the blocked nature of the trials, the subject did not erroneously report the order of the clicks. Thus, subjects were in effect reporting where a known order becomes subjectively indistinguishable. This blocked presentation order was used because in this way the task of discriminating order was separated from the detection of side of stimulation. Moreover, Efron (1963) reported that blocked conditions of stimulus presentation in a similar task minimized the variance within a subject's performance.

Results

To obtain the point at which temporal order discriminations could no longer be made, the mean value of the interval within which apparent simultaneity occurred was calculated for runs in which the right-ear pulse was delivered first and for runs in which the left-ear pulse was delivered first. The data for individual subjects are shown in Table 1. The mean threshold of temporal order for the right-first runs was 54.9 msec and for the left-first runs was 60.6 msec yielding a difference of 5.7 msec between conditions. A matched-pairs t-test comparing right-first and left-first scores for each subject showed the mean ear difference to be significant at the .01 level (t (9) = 4.19). Ninety-five per cent confidence limits for the population ("true") ear difference were 2.782 and 8.618. A lower threshold of temporal order in right-first runs was obtained for each of the 10 subjects tested, and there was no practice effect found as a function of run order. These data are presented in Table 1 and Table 2.

Part B

The method of constant stimuli was used to determine the threshold at which a correct order judgment was made on 75 per cent of the trials.

Subjects

A new sample of 10 right-handed college students were paid for participation in the experiment. All were within an age range of 18 to 25 years and reported normal hearing.

Apparatus

Grason-Stadler 1200 series modules were used to time the entire sequence during a trial. The subject started the sequence by pushing a button from the subject station when ready, triggering the Grason-Stadler timer. The timer then sent a triggering pulse to two Tektronix pulse generators which produced the auditory clicks.

Procedure

A click was delivered to the left or the right ear of a subject. After a randomly-chosen temporal interval, the other ear received a click. Five intervals were used (10, 20, 30, 40, and 50 msec) and each interval was presented 20 times in a right-first condition and 20 times in a left-first condition. A total of 240 trials were given in the experiment with 100 test trials and 20 practice trials per day. A blocked presentation order was again used in which all right-first trials were given on one day followed by the left-first trials on the second day. This order was counterbalanced across subjects. The instructions given to the subject were similar to those presented in Part A. In contrast to Part A, the

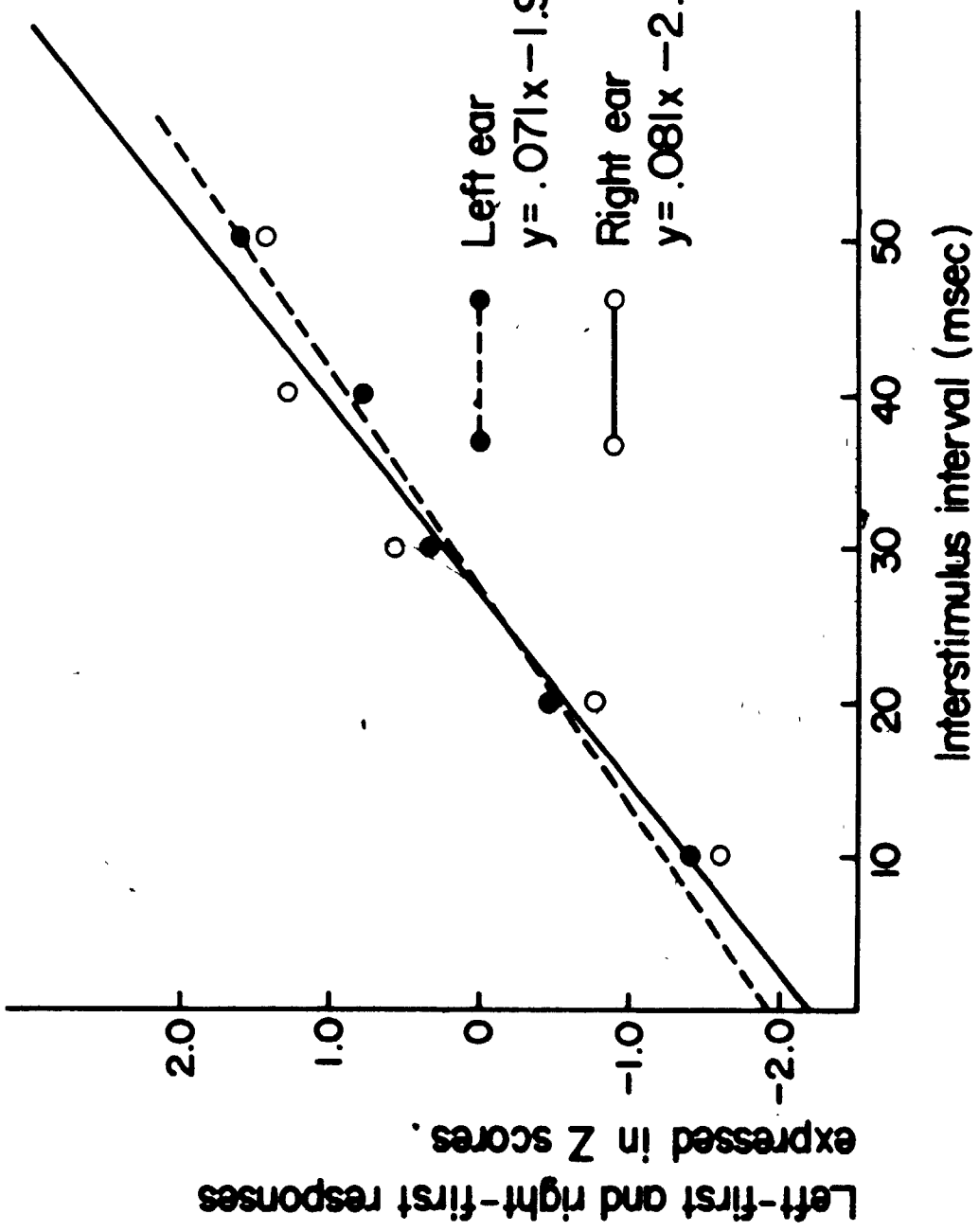
subject made a manual response with the right hand to indicate successive order or "simultaneity" prior to a verbal response saying which ear received the first click in the case of a successive-order judgment. The manual response consisted of pushing one button on the subject station to indicate successive order and a different button to indicate "simultaneity".

Results and Discussion

The value at which a correct-order judgment was obtained on 75 percent of the trials was derived for each subject using linear interpolation between the two interstimulus intervals which bracketed the threshold. The mean threshold across subjects was 35.3 msec for left-first trials and 32.2 msec for right-first trials. The difference of 3.1 msec was significant at the .05 level ($t(9) = 2.4206$). Eight of the 10 subjects tested showed a difference in this direction. In addition, a straight line was fit to the means for each interstimulus interval using linear regression and is shown in Figure 1.

The data obtained from part A and part B both show a higher threshold for temporal order discrimination when the left stimulus is presented prior to the right stimulus, than shown for the opposite order of presentation. Both sets of results are consistent with the hypothesis that the locus of processing for this task is in the left hemisphere. The difference between the left-first and the right-first condition was 5.7 msec in part A and 3.1 msec in part B. The smaller difference observed in part B may partially result from the inclusion of the data from the two subjects who showed lower thresholds for the left-first condition. It can be demonstrated (See Appendix A) that

Figure 1 Probability of left-first and right-first responses at each value of interstimulus interval expressed in z-scores.


Left ear
y=.071x−1.92
Right ear
y=.081x−2.18
Left-first and right-first responses
expressed in Z scores.
2.0
1.0
0
−1.0
−2.0
10
20
30
40
50
Interstimulus interval (msec)

one-half of the difference between thresholds obtained for the left-first and right-first conditions provides an estimate of interhemispheric transfer time. For the eighteen subjects combined in part A and part B who obtained a lower threshold for the right-first condition, the transfer was hypothesized as occurring from the right hemisphere to the site of temporal processing in the left hemisphere. However, for the two subjects who obtained a lower threshold for the left-first condition the transfer may have occurred from the left hemisphere to the right hemisphere. That is, the determination of temporal order may have been made in the right hemisphere for these two subjects. Therefore, to consider one-half of the difference in thresholds obtained as an estimate of transfer time, it would be more appropriate to base the estimate on the absolute value of the threshold difference. When this transformation is made, then the value of the mean threshold difference obtained in part B is 4.4 msec and the estimate of transfer time is 2.2 msec. The difference between mean estimates of transfer time thus obtained for part A (2.8 msec) and part B (2.2 msec) was nonsignificant ($t(18) = 1.31857$).

The findings of Experiment I are in agreement with Efron's (1963a) similar study of visual and cutaneous stimulation and with Hirsh and Sherrick's (1961) study in the auditory modality, in the direction of the ear difference. Any differences in mean threshold estimates between parts A and B may reflect methodological differences. The untrained subject typically obtains thresholds of 60 msec for this task (Edwards & Auger, 1965; Hirsh & Fraisse, 1964). In contrast, the trained subject

may obtain a threshold value of 20 msec (Hirsh & Sherrick, 1961). The training due to an increased number of trials in part B, compared to part A, provided a lower estimate of the absolute threshold. However, the relative difference in threshold for the left and the right ear rather than the absolute threshold is the measure which is pertinent to the hypothesis of the experiment, and the two techniques provided similar estimates of this difference.

EXPERIMENT II

Reaction Time to the Offset of Pulse Trains

This experiment was conducted to investigate the left hemisphere's role in processing the temporal interval or duration between two pulses in a train. Previous studies of normal subjects have shown that perception of temporal order and tonal sequences yields a right-ear advantage (Halperin et al., 1973; Papçun et al., 1974). While the tonal sequences involved perception of differences in duration, this was confounded with perception of temporal order. The examination of duration discrimination in normals with respect to hemispheric asymmetry seemed necessary, in particular, to determine the critical range of duration values involved in the demonstration of a right-ear advantage. Clearly, critical ranges determined with brain-damaged subjects would not be generalizable to normal subjects.

A sequence of pulses was presented to either the left

or the right ear simultaneously with a distinguishable pulse sequence in the other ear. Reaction time (RT) to the offset of the sequence was measured. It was expected that RT would be shorter for sequences delivered to the right ear if the left hemisphere was primarily involved in the processing. The rationale for this expectation, in more detailed terms, is the following: To determine the end of a sequence, the subject must process the duration between pulses in order to know there is not another pulse and that the sequence has ended. If this processing occurs in the left hemisphere, then information related to the time of occurrence of each pulse will be transferred from the right hemisphere to the left hemisphere following left ear stimulation. The transfer will be reflected in a greater RT value for sequences delivered to the left ear. Since information related to the time of occurrence of right-side stimulation arrives directly in the left hemisphere, there will be no transfer time involved in the resulting RT value. (This rationale is presented schematically in Appendix C.)

Pilot work using auditory stimuli indicated that the duration of the interval between clicks in a sequence was of key importance in determining whether a smaller RT value for the right ear or no difference in RT between ears was found. A difference in RT values for sequences presented at a rate of 10 pulses per second was not observed between ears, however, sequences delivered at a rate of 20 pulses per second yielded a significant right-ear advantage

(t (8) = 2.68, $p<.05$). These data suggested that both hemispheres may be processing temporal intervals of 100 msec but that the left hemisphere may be more involved in the processing of smaller intervals. To further investigate this finding, the presentation rate of pulse sequences was varied in order to determine the interpulse duration at which an ear difference could be revealed, and from which hemispheric specialization could be inferred.

Subjects

A total of seven subjects ranging in age from 18 to 25 years were paid for participation in the experiment. They reported normal hearing and were right-handed as indicated by the questionnaire (See Appendix B.)

Apparatus

The experimental pulse trains were produced by modules of the Haer digital stimulator system, while the contralateral competition pulses were produced by Tektronix waveform and pulse generators. A Hewlett-Packard oscilloscope was used to calibrate the pulses. The stimuli were directed to the left or right channel of stereophonic headphones. A Hewlett-Packard counter-timer was used to measure RT; it started when the last pulse was generated and was stopped by the subject's response.

Procedure

This experiment was initially conducted with four subjects, therefore, the procedure immediately described applies to four subjects. Slight changes were introduced

in the control conditions for the remaining three subjects. They are specified at the end of the procedural description.

Sequences of 1 msec square wave pulses were presented at each of four presentation rates to either the left or the right ear at an average intensity of 80 dB SL. At the same time, the contralateral ear was presented with a competing stimulus consisting of a recurrent 1 msec square wave pulse presented at 100 Hz with an average intensity of 55 dB SL. The presentation rate of 100 Hz was chosen for the competition stimulus so as to be distinguishable from the experimental sequence and its intensity was determined by the subject to be equal to the intensity of the pulse train. The reason for providing the contralateral pulse sequence was to provide dichotic stimulation and thus facilitate the use of the contralateral auditory pathways. In each trial the recurrent competition pulse started before the experimental sequence and continued on slightly longer so that RT would be uninfluenced by its offset.

The experimental sequences were composed of nine different lengths (2, 3, 4, 5, 7, 8, 10, 12, or 15 pulses per sequence), each randomly presented twice within a block of 18 trials. The difference in sequence length was introduced as a control measure to prevent the subject from anticipating sequence termination. For each presentation rate, the experiment included 288 trials (16 blocks); one-half of these were delivered to each ear. The order of presentation of right or left ear trials was given in a

prearranged sequence of randomized blocks such that the maximum number of blocks delivered successively to one ear was not greater than two. The left hand was used to respond to one-half of the trials to either ear and the right hand for the other half. The order of hand use was counterbalanced within subjects. The subject was informed prior to a sequence presentation, which ear would be stimulated and which hand was to be used in the response. The RT response was made with the thumb on the top of the hand-held switch and the fingers were curled around the handle to minimize their movement.

The four presentation rates employed were 10 pulses per second, 15 pulses per second, 20 pulses per second, and 25 pulses per second. The order of rate presentation was counterbalanced across subjects.

Each subject was given 72 practice trials at the beginning of an experimental session and received a total of four experimental sessions. A session consisted of 288 trials at one rate of presentation: 72 for each ear-hand combination.

For three subjects, procedural changes were the following: five lengths of either 2, 4, 8, 12, or 16 pulses per sequence were presented. Thus the total number of trials was 280: 70 for each ear-hand combination. In all other respects the procedure was identical for the subjects. The changes were made in order to simplify the experimental protocol.

Results and Discussion

The data for seven subjects were pooled for analysis since initial inspection showed no apparent differences as a result of the slight procedural changes.

An analysis of variance was computed with repeated measures on the factors of ear (left and right) and rate (10, 15, 20, and 25 pulses per second). The summary table for the analysis of variance is shown in Appendix D. The overall mean RT value for sequences presented to the left ear (mean of 291.9 msec) was not significantly different from the RT value for sequences presented to the right ear (mean of 289.2 msec). A significant difference in RT was observed between rates of presentation; faster rates were responded to more quickly than slower rates ($F(3, 18) = 18.69$, $p < .001$). An interaction of ear and rate was significant at a confidence level of .05 ($F(3, 18) = 4.586$). A Neumann-Keuls test on the means indicated RT was shorter for the right ear compared to the left at the 20 per second rate and 25 per second presentation rate. For the 10 per second and 15 per second presentation rates mean differences did not reach significance. In fact, the two ears showed almost identical RT at 15 pulses per second and the left ear had a smaller mean value at 10 pulses per second (See Table 3a).

The results indicate that the left hemisphere is predominant in processing interpulse durations of 40 msec and 50 msec whereas both hemispheres are apparently involved

in processing interpulse durations of 67 msec and 100 msec. The difference in RT values between the left and the right ear at the faster rates may be assumed to reflect the inter-hemispheric transfer time of temporal information. A more detailed discussion of this conclusion will follow in the general discussion.

The use of the left and the right hand was a control measure to insure that neither hemisphere gained an advantage from a more direct control of motor output, and therefore was not included in the main analysis. Nevertheless, an analysis of variance computed for hand and rate factors showed the right-hand response was significantly faster than the left-hand response at each rate of presentation (F (1,6) = 13.007, $p < .001$). (See Table 3b)

The decline in RT with increase in presentation rate for the rates of 10, 15, and 20 pulses per second indicated that the subject was performing the task as hypothesized. The reason for the failure to find a corresponding decrease in RT for the 25 pulse per second rate is unclear. Nevertheless, the systematic decrease for the three slower rates suggests that the value of the duration between clicks was the feature of the task to which the subject responded.

EXPERIMENT III

Discrimination of Duration

The ability to detect small differences in duration was investigated to further examine the role of the left

cerebral hemisphere in processing temporal duration within the confines of a new task. A delayed-comparison task was employed similar to that employed in studies of brain-damaged subjects. Two durations were presented to the left or to the right ear and subjects were required to report which stimulus was judged to be longer. The duration differences between pairs of stimuli varied from 0 msec to 15 msec.

It was anticipated that, if the left hemisphere was primarily responsible for discrimination of small duration differences, the accuracy of difference judgments would be greater for durations presented to the right ear than for durations presented to the left ear. The hypothesized superiority of report for right-ear stimulation was based on the assumption that contralateral ear-hemisphere pathways would be used for the transmission of stimulus information. Under these conditions, durations presented to the left ear would be subject to transcallosal degradation and arrive at the left hemisphere processing site in a degraded form. If callosal transfer acts to impair the perception or identification of stimuli, then overall accuracy of judgments based on those stimuli would be lowered and difference thresholds would be greater.

Subjects

A sample of four subjects, tested in Experiment II, were paid for participation in this experiment.

Apparatus

The experimental sequences were produced and timed by modules of the Haer digital stimulator system and contralateral

pulses were produced by Tektronix waveform and pulse generators. The subject listened to the stimuli through stereophonic headphones.

Procedure

Two trains of 1 msec square wave pulses were presented to either the left ear or the right ear at a rate of 50 pulses per second, and at an intensity level of 80 dB SL. A 1 msec recurrent pulse was presented to the contralateral ear in order to create competition between ears and enhance the use of the contralateral pathways. It commenced slightly before the experimental sequences and terminated after their presentation. Its presentation rate was 20 pulses per second which allowed it to be clearly distinguished from the experimental sequence. The subject was asked to listen to both sequences in the tested ear and then report the longer one.

The method of constant stimuli was used to present the sequences. A base duration of 200 msec was the standard stimulus, and comparison durations varied from 185 msec to 215 msec in steps of 5 msec. Thus, a total of seven comparison durations was employed. A preliminary study was conducted to choose specific values for the comparison durations. The initial range included increments of plus or minus 75 msec but discrimination was almost errorless for values greater than 15 msec. The standard stimulus was placed in the first and second position an equal number of times.

There were two temporal intervals between sequences (ISI); for one-half of the trials ISI was 2.5 sec and for one-half ISI was 5 sec. The total number of trials given per subject was 840. There were 30 presentations of the standard with itself and with each of the other comparison durations, for each ear and for each value of ISI.

The presentation of comparison durations followed a prearranged random order. Trials to the left or right ear were given in blocks of 14 and the blocks were randomly presented with the restriction that at no time were more than two given consecutively to the same ear. One-half of the subjects received the 2.5 sec ISI first and one - half received the 5 sec ISI first.

Each experimental session consisted of 140 trials preceded by 25 practice trials.

Results and Discussion

The data were scored for the number of correct longer judgments and an analysis of variance computed. The factors of classification were: ear (left and right), value of the comparison duration (above or below the standard duration), and the intersequence interval (2.5 sec and 5.0 sec). A summary table of the analysis is provided in Appendix E.

The main effects of ear, value of comparison duration and intersequence interval were nonsignificant. However, a significant interaction between the value of comparison duration and intersequence interval was obtained (F (1,3) = 25.585, $p<.001$). This interaction suggests that the

subjects were less accurate in their judgments of comparison durations below the value of the standard duration at the 5.0 sec ISI but not at the 2.5 sec ISI.

Because of the few degrees of freedom, the failure to obtain significance with an analysis of variance does not provide a crucial test of possible differences. In order to make use of the large number of trials received by each subject, t-tests were computed on individual subject data. That is, possible ear differences were examined within each block of 14 trials for the 2.5 sec ISI and for the 5.0 sec ISI. Even assuming independence of observations as this statistical test required, no significant ear differences were found.

Inspection of the data did, nevertheless, suggest the presence of one consistent pattern occurring for both ears. It appeared that the subjects judgments were more accurate on those trials within which the longer of the two stimuli, whether standard or comparison, preceded the shorter. Accordingly, the data were cast into a second analysis of variance. The factors of classification were: presentation order (long, short and short, long) and intersequence interval (2.5 sec and 5.0 sec). The analysis showed that accuracy of report was greater for the long - short pairings (mean of 140.2/ maximum possible = 210) compared to the short - long pairings (mean of 113.8/ maximum possible = 210), although it was of marginal significance (F (1,3) = 6.62, $0.1 > p > .05$). The interaction of presenta-

tion order and intersequence interval was also marginally significant (F (1,3) = 6.717. $0.1 > p > .05$). This interaction was tested with an *a posteriori* t-test showing that accuracy for long - short pairings was significantly better at the 2.5 sec ISI compared to the 5.0 sec ISI (t (3) = 3.087, $p < .05$). The difference between the short - long pairings as a function of ISI was in the opposite direction and nonsignificant (t (3) = 0.5143). The observation of greater accuracy for long - short pairings and the interaction with sequence interval is of theoretical interest for the processing of duration, apart from the subject of laterality.

The difference thresholds are presented for individual and combined subjects in Table 4. Inspection of these data suggests no consistent pattern favoring the left or the right ear. However, it does appear that smaller difference thresholds were obtained for both left and right ears at the 2.5 sec ISI than at the 5.0 sec ISI.

The results of the present experiment do not support the hypothesis that discriminations involving small differences in stimulus duration are localized within the left hemisphere. Nor, however, do these results force rejection of that hypothesis. It was initially argued that, if the left hemisphere were specialized for such tasks, left ear stimulation would arrive at the site of processing in a degraded form relative to right-ear sequences because of transcallosal information loss. The noise introduced in left-ear signals was expected to decrease the accuracy with

which they were processed in the left hemisphere and hence lower left-ear performance. Contrary to expectation, accuracy of report was slightly higher for the left ear (72%) than for the right ear (69%). Nevertheless, it might be argued that since both the standard and the comparison stimulus sequences were presented to the left ear, both would have been degraded. If the effect of this degradation was systematic in that it produced a consistent change in the perceived duration, this systematic distortion of the stimulus would leave the relative duration of the standard and comparison sequences unaffected. Thus, a comparable left ear and right ear performance level would be expected. Therefore, it remains possible that the left hemisphere is indeed functionally dominant for processing small differences in stimulus duration though the procedure employed was not sufficiently sensitive to render such specialization accessible to measurement.

Experiment IV was designed to provide a more sensitive test of possible left-hemisphere specialization for processing temporal duration.

EXPERIMENT IV

Discrimination of Duration in a Monaural Task

A monaural recognition task was employed in order to investigate left and right hemisphere processing of small differences in duration. A stimulus of standard duration was presented binaurally followed by a comparison duration presented monaurally to either the left or the right ear.

Unlike Experiment III, in which both standard and comparison duration were monaurally presented, the present procedure provided a means of separating the paths of transmission of standard and comparison durations. Presumably, the binaurally presented standard duration would be directly transmitted to both cerebral hemispheres whereas the monaurally presented comparison duration would initially be transmitted to the contralateral hemisphere, arriving at the ipsilateral hemisphere only after callosal transfer. Thus, by confining potential transcallosal stimulus degradation, or distortion as previously suggested, to the comparison duration, the source of confounding described in Experiment III should be avoided.

Subjects

A new sample of ten right-handed college students was tested and paid for participation. Each reported normal hearing and was given the handedness questionnaire (Annett, 1970).

Apparatus

Output of the Haer stimulator system was used to produce the stimulus sequences of 1 msec square wave pulses. All sequences were prerecorded on an audio tape. The subject listened through stereophonic headphones and gave a verbal response.

Procedure

A standard duration of 250 msec was played binaurally followed by a comparison duration of either 210, 230, 250,

270, or 290 msec presented monaurally at random to the left or the right ear. The interval between the onset of the standard and the comparison duration was 2.5 seconds. The subject was required to report whether the comparison duration was the same, shorter, or longer than the standard duration. A total of 150 trials was given: 75 with comparison durations to the left ear and 75 to the right ear. The first 30 trials were considered as practice trials and not scored in the data analysis. The headphones were reversed for one-half of the subjects to control for any asymmetries in the audio channel.

Results and Discussion

An analysis of variance with repeated measures was computed on the data. The factors of classification were: ear (left and right) and duration (210, 230, 250, 270, and 290 msec). The summary table of this analysis is shown in Appendix F. Comparison durations heard in the right ear were identified more accurately (mean of 35.9) than were durations heard in the left ear (mean of 31.4). The ear effect was significant at the .01 level (F (1,9) = 12.5). In addition, the shorter durations were more accurately identified than the longer durations for both the left and the right ear (F (4.36) = 33.46, $p < .01$). The psychometric function showing per cent correct responses for the left and the right ear at each comparison duration is shown in Figure 2. Inspection of these data indicates that the right-ear advantage occurred when comparison durations were 250, 270 and 290 msec. No difference between

ears occurred at 210 msec and a small difference in favor of the left ear occurred at 230 msec.

The per cent correct responses for each ear as a function of type of judgment --shorter, same or different-- is shown in Figure 3. The nature of the errors made may be assessed from this graph.

When the comparison duration was 250 msec it was most often judged to be shorter than the standard when heard in either ear, although there were significantly more such errors when heard in the left ear (t (9) = 2.011, $p < .05$). At the longer comparison durations of 270 msec and 290 msec the majority of the errors for both ears consisted of "same" judgments. Significantly more "same" judgments were shown for the left ear responses at the 270 msec value (t (9) = 2.2298, $p < .05$) but the difference did not reach significance for the 290 msec value (t (9) = 1.0078, $p > .05$). As a consequence, a constant error was shown for the left ear but not for the right ear. The left ear point of subjective equality was at 270 msec.

One conclusion suggested by these results is that a systematic type of information loss, or distortion, did occur for both ears but was of a larger magnitude for the left ear. This conclusion is made evident from the pattern of errors showing that a comparison duration equal to the standard was judged "shorter" whereas comparison durations longer than the standard were judged the "same" as the standard. The superior identification shown for trials in which the longer stimulus was presented as the first

Figure 2 Per cent correct responses for the left and the right ear at each value of the comparison duration.

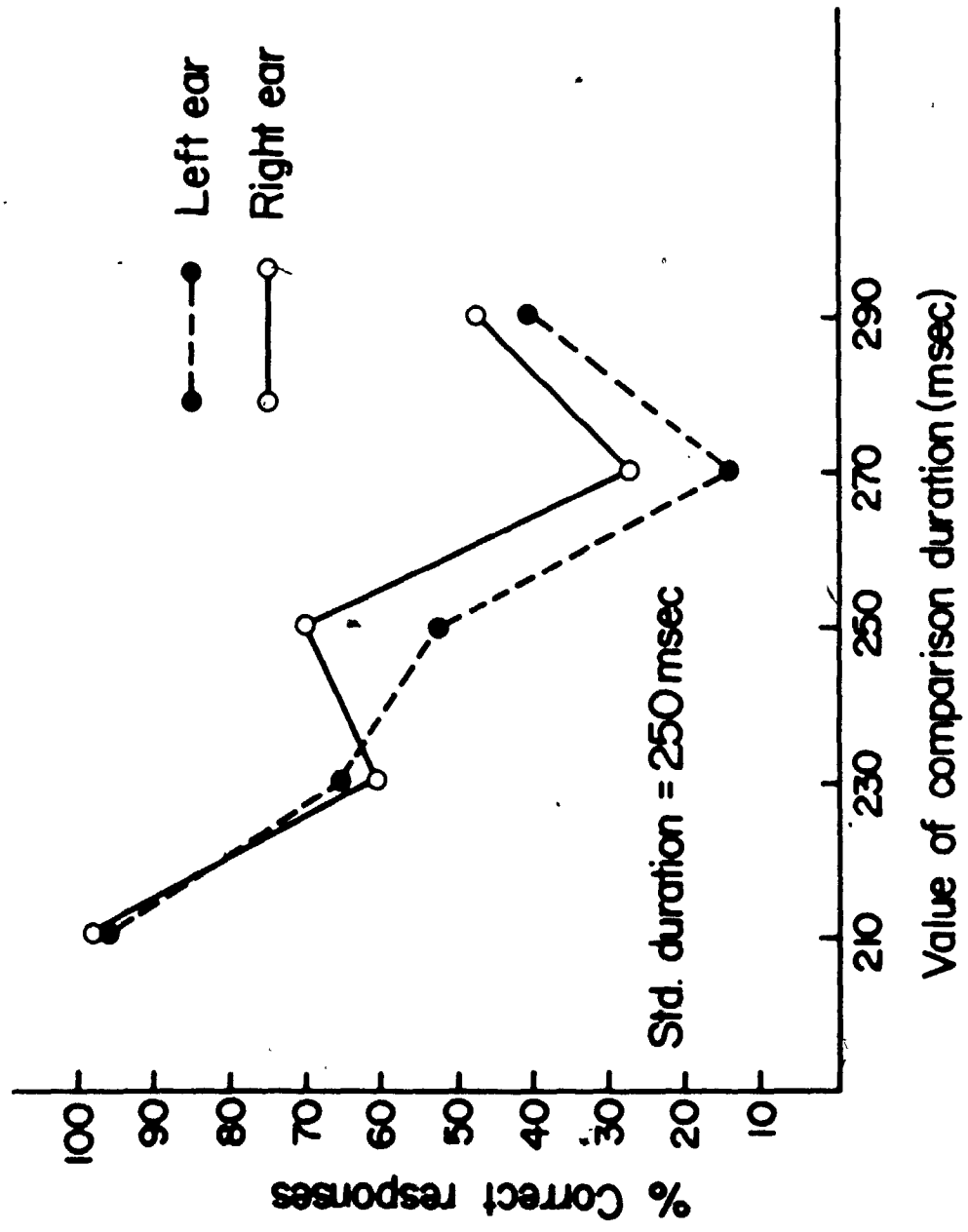
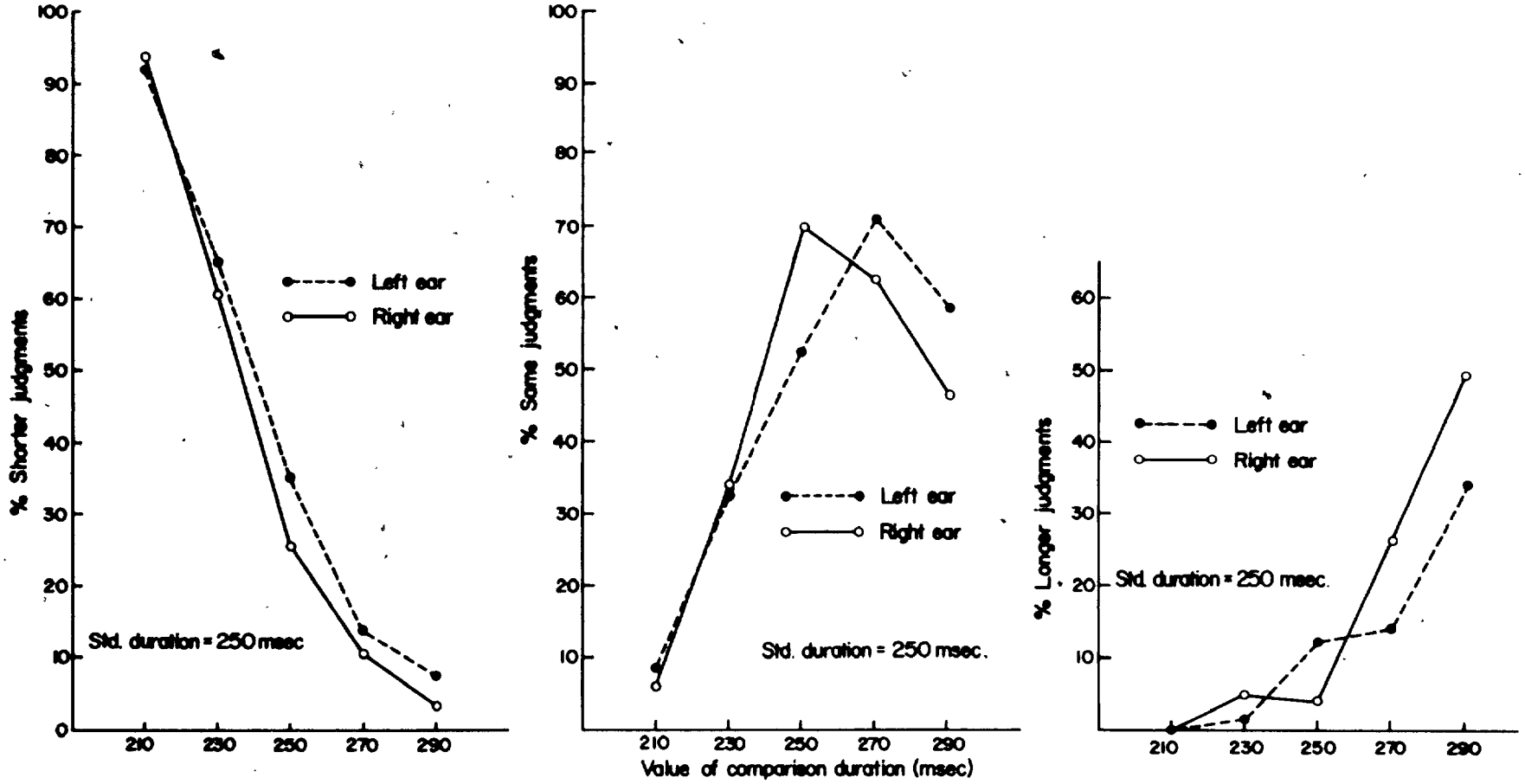

Left ear
Right ear
Std. duration = 250 msec
% Correct responses
100
90
80
70
60
50
40
30
20
10
210
230
250
270
290
Value of comparison duration (msec)

Figure 3 Per cent correct responses for (a) shorter judgments, (b) same judgments, and (c) longer judgments at each value of comparison duration.


% Shorter judgments
% Same judgments
% Longer judgments
Left ear
Right ear
Std. duration = 250 msec
Value of comparison duration (msec)
100
90
80
70
60
50
40
30
20
10
0
210
230
250
270
290

member of the pair was in accord with the similar finding in Experiment III.

Two interpretations may be made of these results. The first would suggest that information loss due to memory processes (e.g. proactive interference) occurred for both ears and acted to degrade the second stimulus by shortening its perceived duration. Thus, performance when the second duration was shorter than the first was facilitated relative to performance when the second duration was longer than the first. The greater magnitude of this effect when the second stimulus was presented to the left ear is compatible with specifying that the locus of processing is within the left hemisphere. The ear difference at each comparison duration is then in the predicted direction and is suggested to be a result of the greater amount of information loss (i.e. shortening of perceived duration) occurring for left-ear stimuli, presumably due to callosal transmission.

An alternate interpretation of the data would predict the same pattern of results if processing within the right hemisphere were assumed. This interpretation postulates that the memory trace of the first stimulus is degraded in such a manner that its duration is overestimated and that greater overestimation occurs over time. In addition, this alternative account assumes that callosal transmission acts to lengthen the perceived duration of the comparison stimulus. If this were the case then more lengthening should occur for the right-ear stimulus (requiring callosal transmission) than for the left-ear stimulus. As a

consequence, detection of differences in duration would be facilitated for the right-ear stimulus at comparison durations longer than the standard and impaired for comparison durations shorter than the standard. Thus, the greater overestimation of the right-ear stimulus, compared to the left, would act to increase its accuracy in discrimination of durations presented to the right ear.

In choosing between these alternate interpretations of the data, the results from Experiment III are useful. The observation that performance was facilitated in pairings where the long stimulus was presented first interacted with the length of the intersequence interval. In the long - short presentation order there was a significant difference at the 2.5 sec ISI compared to 5.0 sec ISI, showing more accurate performance at the 2.5 sec ISI. For short - long pairings, the difference was in the opposite direction and nonsignificant. This form of interaction is not predictable from an hypothesis suggesting both members of the pair are degraded in the form of overestimation. If this hypothesis were correct, the relative accuracy when the long stimulus was presented first should have been greater at the 5.0 sec ISI than at the 2.5 sec ISI. However, the observed difference was in the opposite direction. Similarly, if it were assumed that both standard and comparison durations were exaggerated, then in the oondition where the short stimulus was presented first, performance at the 5.0 sec ISI should have been poorer than at the 2.5 sec ISI. Once again, the

observed difference was in the opposite direction.

The conclusions from the above analysis increase the credibility of the first interpretation of the ear difference, namely, that the second stimulus was perceptually shortened as a function of memory processes and callosal transmission. The right-ear advantage obtained may, then, be most plausibly interpreted as reflecting left-hemisphere superiority.

CHAPTER III

GENERAL DISCUSSION

The results of the present investigation support previous findings indicating that the left hemisphere may be specialized for processing temporal information. In agreement with Efron's (1963a) report of left-hemisphere superiority in identifying the temporal order of visual and cutaneous stimuli and Hirsh and Sherrick's (1961) data on the identification of temporal order of auditory stimuli, Experiment I demonstrated that identification of the temporal order of nonverbal, auditory stimuli critically involved left-hemisphere mechanisms. The results of Experiment IV indicated that discriminations involving small differences in the durations of auditory stimuli are also dependent upon left-hemisphere processes, thus replicating with normal subjects the left-hemisphere superiority demonstrated in similar tasks with brain-damaged patients (Gordon, 1967; Needham & Black, 1970). In Experiment II, which employed a duration task not previously investigated, it was found that the reaction to the termination of temporally patterned stimuli critically involved mechanisms situated in the left hemisphere.

However, on the basis of the present results the conclusion that the left hemisphere is specialized for auditory temporal discriminations may need to be qualified. The results obtained in Experiment II indicated left-hemispheric specialization for processing stimulus durations only when

those durations did not exceed 50 msec. This finding supports the hypothesis presented earlier, namely, that left-hemisphere specialization for processing duration information may be restricted to a defined range of stimulus durations. If stimulus durations in excess of 50 msec are employed, the left and right hemispheres may be equally capable of responding to such durations, as the results of Experiment II indicate.

The notion that left-hemispheric specialization for duration may be restricted to a critical range is suggested by data obtained with brain-damaged subjects. These studies indicate that beyond certain interstimulus intervals left and right-brain damaged groups perform similarly in tasks requiring identification of the temporal order (Carmon & Nachshon, 1971; Efron, 1963b), or duration (Van Allen et al, 1966) of stimuli. However, the actual interstimulus intervals required for equivalent performance between groups varied considerably from study to study. Unfortunately, due to the general impairment of functioning that accompanies brain damage, it is not possible to derive from these studies an uncontaminated estimate of the range of stimulus durations for which the normal left hemisphere might be specialized. Hence, the relationship between left-hemispheric specialization for processing temporal cues and for processing speech could not be accurately assessed. The present study, employing normal subjects, obtained an uncontaminated estimate of the range of stimulus durations which appear to be critical to left-hemispheric specialization and therefore

provides a basis upon which the relationship between the left hemisphere's role in speech and its role in temporal duration tasks may be elaborated. Initial steps towards that elaboration are taken in a following section.

Task Demands and the Direction of Lateralization

In the present studies it has been suggested that the critical variable determining the direction of lateralization is the temporal processing demanded by the task. This conclusion is consistent with experimental results demonstrating that although a left-ear advantage or no advantage at all may be obtained in tasks requiring the recognition of nonverbal, auditory stimuli (Curry, 1967; Faglioni, Spinnler & Vignolo, 1969; Halperin et al, 1973; King & Kimura, 1972; Murphy & Venables, 1970; Spellacy, 1970), a right-ear advantage results when temporal cues are intrinsic to the task employed (Halperin et al, 1973; Papcun et al., 1974).

The view that direction of lateralization depends upon the type of processing demanded by the task receives additional support from a study reported by Bever and Chiarello (1974). Musically-naive and musically-experienced subjects received monaural presentations of melodic line excerpts. Consistent with frequent reports of a left-ear advantage in melody recognition tasks (Kimura, 1964; King & Kimura, 1972; Spellacy, 1970), the naive subjects demonstrated a left-ear advantage for retention of melodic line.

The musically experienced subjects, however, demonstrated a right-ear advantage for retention of melodic line. Bever and Chiarello speculated that this atypical right-ear advantage was a result of the manner in which musically experienced subjects processed the melodies. They argued that these subjects were analytical in their identification and attended particularly to the tonal transitions within the melody. The analytical comprehension of melodic line corresponds to an identification based, in part, on temporal cues within the sequence. Thus, the right-ear advantage obtained is consistent with the results and interpretation of the present study.

The hypothesis that the direction of lateralization depends upon the nature of stimulus-processing required within a task may provide a partial account of the lateralization patterns obtained with verbal stimuli. It was previously noted that a right-ear advantage is not usually obtained in dichotic listening tasks when subjects are presented with steady-state vowels (Studdert-Kennedy & Shankweiler, 1970). However, Spellacy and Blumstein (1970) have demonstrated that a right-ear advantage for the identification of vowels can be induced by manipulating the context within which they are presented. Consonant-vowel-consonant (CVC) nonsense trigrams were dichotically presented to subjects under one of two experimental conditions. In a language-set condition, presentation of the CVC nonsense syllables occurred within a list of CVC real words.

In a nonlanguage-set condition, the CVC nonsense syllables were intermixed with a number of nonlanguage sounds. Subjects in both conditions were required to identify the vowel in each CVC nonsense trigram. The results indicated a left-ear advantage for identification of the vowels in the nonlanguage-set condition, but a right-ear advantage in the language-set condition. Apparently, then, the vowels were processed in the left or the right hemisphere depending upon the processing set required by the stimulus-context within which they were presented. Spellacy and Blumstein also reported a right-ear advantage for the consonants contained in the CVC nonsense trigrams which held across the language-set and nonlanguage-set conditions. The inability to influence left-hemispheric lateralization of these stimuli by manipulating the context is consistent with the hypothesis that consonants are discriminated primarily on the basis of their intrinsic temporal cues (i.e. formant transitions) and that the perception of temporal cues may necessarily involve left-hemisphere mechanisms.

Seamon (1974), employing an experimental task which differed from that of Spellacy and Blumstein (1970), has provided additional evidence pointing to the role of task requirements as a determinant of the direction of lateralization. Subjects were exposed to a list of words presented visually in free-field followed by a probe to either the left or right visual field. The probe consisted of a picture of one of the words contained in the list. Subjects were

requested to identify the probe as belonging or not belonging to the preceding list and their reaction times were recorded. The task was presented to the same subjects under two sets of instructions. In the first set, subjects were instructed to rehearse each list of words subvocally until the probe occurred. In the other set, subjects were instructed to relate the words by combining them into a unified image. The results indicated faster reaction times to probes presented to the left hemisphere under the rehearsal instructions and faster reaction times to probes presented to the right hemisphere under the relational instructions. In discussing the results, Seamon argued that the relational instructions encouraged the use of parallel processing since the reaction times did not increase as a function of the number of words contained in a list. However, since reaction times did increase with list length under the rehearsal instructions, Seamon argued that the rehearsal instructions encouraged the use of serial processing. The point of primary interest for the present discussion is that the verbal stimuli employed demonstrated a different direction of lateralization depending upon the type of processing required for the task. Moreover, it is of some interest that the left-hemisphere advantage was observed only when the instructions encouraged the use of serial processing.

Interpretation of Threshold and Reaction Time Ear Differences

The results of Experiment I and Experiment II indicated a left-hemisphere advantage in tasks requiring subjects to identify the temporal order of auditory stimuli or to react to the offset of temporally patterned auditory stimuli. Experiment I, which examined the perception of successive order, yielded absolute differences in thresholds for the left-ear condition versus the right-ear condition of 5.7 msec (part A) and 4.4 msec (part B). In Experiment II, it was found that reaction time to the offset of pulse sequences was greater for the left-ear condition than for the right-ear condition by 6.2 msec at the 20 per second presentation rate and by 8.4 msec at the 25 per second rate. It was suggested that the reaction-time differences and one-half of the threshold differences provide an estimate of the time required for temporal information to be transferred from the right hemisphere to a site of processing within the left hemisphere. In fact, the range of values obtained for this estimate, from 2.2 msec to 8.4 msec, is consistent with estimates of interhemispheric transfer time previously reported for auditory, visual and cutaneous stimulation (Catlin & Neville, 1976; Efron, 1963a; Hayden & Spellacy, 1972; Jeeves & Dixon, 1970). This interpretation of the time difference is based on the assumed use of the contralateral pathways shown to be functionally prepotent over the ipsilateral in a dichotic task (Milner et al., 1968). There are, however, alternative interpretations of the

threshold and reaction-time differences which need to be considered.

One possible alternative interpretation suggests that the right hemisphere has a slightly higher temporal-order threshold than the left and in the left-first trials only the right hemisphere performs the task so consequently, only its threshold is being measured. Specifically, if the right hemisphere performed the tasks slightly more poorly than the left hemisphere, then the threshold and reaction-time differences obtained in Experiments I and II might reflect these differential thresholds rather than providing an estimate of interhemispheric transfer time. With reference to Experiment I, a discussion of the experimental data may aid in evaluating the notion that the right hemisphere has a slightly higher threshold than the left hemisphere. Although this possibility could not be directly assessed with the normal subjects in the current task, the plausibility of this interpretation of the obtained differences may be questioned.

Previous studies of right and left-brain damaged subjects employing a task similar to that used in Experiment I, found differences in successive-order thresholds ranging from 10 msec to 354 msec. Clearly, these differences are in excess of the 5.7 msec and 4.4 msec differences obtained in Experiment I. The results from the clinical studies (Edwards & Auger, 1965; Efron, 1963b; Swisher & Hirsh, 1972) suggest that right-hemisphere processes for this task are slower by a much larger order of magnitude than suggested by an average

difference of 5 msec. While conceivable that a very small difference between thresholds of the right versus left hemisphere could exist in normal subjects, it seems more reasonable to accept the 5 msec difference in thresholds that was obtained in Experiment I as an estimate of transfer time.

In the studies of brain-damaged subjects cited above, it remains possible that the larger thresholds associated with left-brain damage do not indicate performance of the right hemisphere. Instead, the damaged left hemisphere may have been performing the task but much more poorly than if it were intact. If this were the case, then the function could be considered to be strictly localized in the left hemisphere, the right hemisphere having no potential for temporal-order processing.

While it is unlikely that the difference in thresholds of Experiment I reflects the difference in the threshold of the right versus the left hemisphere, it remains possible that both hemispheres processed the information, but that the right hemisphere's responses were much slower than the left hemisphere's responses. On this basis, the left hemisphere would be quicker to make a judgment and thus, only the left hemisphere function would contribute to the measurement. Given this possibility, the difference in Experiment I provides an estimate of interhemispheric

transfer time not because the processing is localized exclusively in the left hemisphere, but because only its function in responding is being tapped. That is, the right hemisphere's correct judgments concerning temporal order were always lost because the left hemisphere responded faster. The possibility of equal temporal-order thresholds between the hemispheres but slower right-hemisphere responding might then, in principle, be incapable of disproof in studies of normal subjects. But as has been noted above, clinical studies strongly indicate that the right hemisphere is actually inoapable of discriminating small differences in order.

In Experiment II, measuring reaction time to sequence offset, analysis of the handedness data does not suggest any right hemisphere processing of the rates for which an ear difference was found. If the interpulse duration of 40 msec or 50 msec were merely processed more slowly in the right hemisphere, then it might be predicted that the left-hand response would be faster than the right for left-ear stimulation. Since the processing would be occurring in the right hemisphere, the left-hand response would also be initiated from the right hemisphere whereas the right-hand response would be initiated from the left hemisphere thus requiring interhemispheric transfer. The left-hand response would gain an advantage over the right-hand response when the right hemisphere was the site of processing. The opposite results were in fact obtained; a consistent right-hand advantage was found across ears at

each presentation rate. It is perhaps noteworthy that a smaller difference between hands was observed at the 10 and 15 pulse per second rates for which bilateral processing was hypothesized. This finding suggests that the left hand was in fact favored by the occurrence of right-hemisphere processing.

Interpretation of Ear Differences in Monaural Tasks

The results of Experiment IV indicated that monaural discrimination of duration differences occurred predominantly within the left hemisphere. Given the use of monaural rather than dichotic stimulation, however, it may be profitable to examine the assumption upon which this conclusion rests and possible alternative accounts of the data obtained.

Investigations employing dichotic stimulation frequently interpret the obtained right-ear advantage for verbal stimuli as reflecting left-hemisphere specialization. First, it is assumed that dominance of contralateral auditory pathways results from suppression of ipsilateral pathways; second, it is assumed that information which arrives directly at its processing site is most accurately identified (Kimura, 1967).

With reference to the first assumption, the use of monaural stimulation requires only the assumption that contralateral ear-hemisphere pathways are stronger than the ipsilateral, without additional inferences concerning

possible suppression of the ipsilateral connections. Given this assumption, a right-ear advantage may be attributed to left hemisphere superiority of processing. Consider the following possibilities: (1) If both pathways were used and information which arrived directly at its processing site was most accurately identified, then no ear difference would be expected provided both hemispheres were equally equipped to process the information. A left-ear advantage would be expected provided the right hemisphere was specialized, and a right-ear advantage would be expected provided the left hemisphere was specialized. (2) If the direct route to the processing site was favored, implying a predominant use of ipsilateral or contralateral pathways (See Catlin, Vanderveer & Teicher, 1976), then a left-ear advantage would be expected if the right hemisphere were the processing site and a right ear advantage would be expected if the left hemisphere were the processing site. As a consequence, time differences in a monaural task would not necessarily be attributable to interhemispheric transfer time. Nevertheless, an obtained ear difference would be attributable to a predominant sampling of hemispheric function although the question of which pathways were employed would be uncertain.

Left Hemisphere Specialization for Temporal Cues of a Critical Order of Magnitude.

A specific hypothesis of this research suggested that

the order of magnitude of temporal cues within a nonverbal temporal discrimination would be critical to the demonstration of a left-hemisphere superiority. The merits of this hypothesis may be assessed from Experiment II. Reaction - time measurements were smaller for the right ear than for the left ear when the duration between pulses in a sequence was 40 msec or 50 msec, but were not smaller for interpulse durations of 67 msec or 100 msec. A left-hemisphere superiority was indicated for processing of the shorter durations whereas both hemispheres appeared involved in processing the longer durations. These results suggest that values of duration which approximate 50 msec or less are critical in engaging left-hemisphere mechanisms.

The kind of temporal analysis required in this task was the processing of a silent duration enclosed between two clicks. This task may be comparable to temporal discriminations involved in identification of some individual speech sounds or phonemes since a similar order of magnitude of critical durations is reported. Liberman, Delattre, Gerstman and Cooper (1956) for example, reported that a formant transition of 20 msec was found to cue the identification of /b/ in the syllable /ba/, but when the same transition was extended to 40 msec, a /w/ was identified. Comparable results were reported for the identification of /g/ and /j/. In this instance/g/ was identified when the formant transition was 30 msec and /j/ was identified when the transition was extended to 60 msec. Liberman,

Harris, Eimas, Lisker and Bastian (1961) reported that the distinction between /p/ and /b/ in the words "rapid" and "rabid" depended upon the duration of the silent interval between the first and second syllable. When the interval was 60 msec, "rabid" was identified; when it was 80 msec, "rapid" was identified.

The above studies indicate that identification of some phonemes appears to be cued by time differences in the order of 20 msec. It is important to note, as well, that each of these verbal stimuli would be lateralized for processing within the left hemisphere (Studdert-Kennedy & Shankweiler, 1970). The importance of these results in the present context stems from their portrayal of a left-hemisphere timing mechanism which is specialized for making very fine temporal discriminations.

The inference of a timing mechanism specialized for durations of this order of magnitude receives further support from studies of verbal processes in brain-damaged subjects. Luria (1966) has described a phonemic aphasia characterized by specific impairment in the discrimination of individual speech sounds and regards this defect as the fundamental source of speech disturbance. Taylor (personal communication, 1976) has similarly observed that left-brain-damaged patients may have difficulty with phonetic identification even in the absence of aphasia as routinely diagnosed.

Studies of the right hemisphere of split-brain

patients are also informative in suggesting that the left hemisphere is uniquely equipped for phoneme recognition. Although these patients may recognize a large number of words and sentences they are specifically impaired in identifying single phonemes (Zaidel, 1977) and in distinguishing phonetic relations (Levy, 1974).

On the basis of these studies and the present findings, it seems reasonable to conclude that the left hemisphere is uniquely specialized for discriminations involving temporal units approximating 50 msec or less.

Although the durations of 40 msec and 50 msec were critical to the observation of a right-ear advantage in the present study and are comparable to durations critical in cueing phoneme distinctions, left-hemisphere specialization based on larger time units obtained in the two studies of normal subjects was discussed in the Introduction. An attempt to account for this difference between the present study and previous studies of normal subjects follows from a consideration of the specific tasks employed.

Halperin et al. (1973) reported a right-ear superiority for recall of dichotically presented tonal patterns containing one or two transitions in duration. The durations presented were 200 msec and 400 msec. In the Papcun et al. (1974) study, a right-ear advantage was obtained for dichotically presented Morse code patterns with units as long as 101.3 msec. In each of these studies a sequence of at least three stimuli was presented. The task, therefore,

required the identification of a temporal sequence rather than a single duration, as required for Experiment II of the present investigation.

To draw an analogy with speech, the basic information unit within the structure of speech sequences is the syllable, not the phoneme, and the duration of a syllable approximates 200 msec (Lenneberg, 1967). It is plausible to suggest that discrimination of temporal sequences of more than two stimuli triggers a different timing mechanism, or mode of operation of the same mechanism, than that triggered for discrimination of phonemes. Furthermore, the critical duration for engagement of this mechanism or mode of operation may be dependent upon a time-unit larger than the phoneme, namely one approximating the duration of a syllable. The suggestion is that the specific parameters of timing processes localized in the left hemisphere are dependent upon the specific demands of the task as well as the structure of the stimulus. When a temporal sequence is presented, it may be discriminated on the basis of a larger time-unit than that critical for discrimination of single durations. The syllable and the phoneme are possible units in speech cueing the different discriminations.

Though the above discussion is speculative, experimental data may be presented in its support. Tallal and Piercey (1974, 1975) have reported results suggesting that accurate identification of isolated phonemes may depend upon the duration of the phoneme. They found that developmental

dysphasics were impaired in the identification of consonants having formant transitions of 43 msec but were able to identify consonants when the formant transitions were increased to 95 msec. As formant transitions are temporal cues, these results support the hypothesis that the discrimination of temporal units below a critical duration of 50 msec selectively involve left-hemisphere mechanisms.

While the Tallal and Piercey (1974, 1975) data support the suggestion that temporal stimulus features within a critical range engage left-hemispheric processes, data indicating left-hemispheric lateralization of shortened and/or distorted steady-state vowels are more difficult to incorporate into a framework stressing temporal analysis. As previously discussed, steady-state vowels are not lateralized to either hemisphere (Studdert-Kennedy & Shankweiler, 1970). However, when steady-state vowels, typically averaging 200 msec in duration, are shortened to less than 100 msec or are embedded within a background of white noise they appear to be processed within the left hemisphere (Godfrey, 1974; Studdert-Kennedy, 1973; Weiss & House, 1973). To account for such data, it has been suggested that vowels increase in perceptual difficulty when shortened or presented against a white-noise background, and approximate the difficulty level of consonants. As a consequence of the increased difficulty, processing time for vowels in echoic memory also decreases to approximate the storage time of consonants (Godfrey, 1974). However, this proposal leaves the basis for

left-hemispheric processing of either consonants or perceptually difficult vowels unspecified.

The present argument suggests that consonants are lateralized on the basis of intrinsic temporal cues. However, the role of temporal cues in the perception of vowels is problematical. It is generally agreed that vowel identification is primarily dependent upon ratio relationships among the vowel's formant frequencies and only secondarily involves parameters such as vowel duration or value of the fundamental frequency (Minifie, 1973, page 254). In the experiments in which the vowels were degraded by white noise (Godfrey, 1974; Weiss & House, 1973) the ratio relationships among formant frequencies would be masked, perhaps necessitating the use of secondary cues, such as vowel duration. This information would be available in the Weiss and House (1973) stimuli since they did not equate vowels for duration but would not be available in the Godfrey (1974) study where vowels were of the same duration.

Recent studies have added temporal characteristics of the vowel waveform to the list of factors affecting the accuracy of vowel identification (Paul & Haggard, 1976; Scott, 1975). Nevertheless, the temporal parameters identified appear to be of an order of magnitude ranging from 2 msec to 10 msec. From temporal acuity studies (Efron, 1973; Hirsh, 1959; Patterson & Green, 1970) it is probable that stimuli separated by intervals as short as 2 to 10 msec interact peripherally providing the cortex with information concerning qualitative features of the stimulation rather than providing temporal

information per se. If, as seems probable, temporal cues in vowel waveforms also interact at the periphery, these stimuli may also provide qualitative rather than temporal information. According to this argument, the problem posed by left-hemispheric lateralization of distorted vowels remains unresolved, despite the presence of potential temporal cues.

Experiment IV investigated monaural discrimination of differences in duration of 20 msec and 40 msec. In this task the temporal discrimination is made on the basis of duration differences rather than absolute durations, yet it is proposed that both tasks would require, among other things, a common mechanism in the left hemisphere which would process durations in the critical range. In Experiment IV the value of the duration differences could not be sufficiently increased to test for a critical range of differences without producing a ceiling effect for responses from the left and the right ear. The paradigm, however, would be useful for testing the hypothesis if the value of the standard duration was increased. In the present study it was 250 msec, but if it was increased to a value producing incorrect discrimination of comparison durations differing from the standard by more than 50 msec, an ear difference would not be predicted. Such a study is currently being conducted and the results, although incomplete, are supportive of this prediction.

In auditory tasks of temporal sequencing, evidence indicating a critical range of durations has also been demonstrated. The work of Tallal and Piercey (1973)

may be reported in illustration of these findings. They presented tonal patterns containing one to four tones, to children with developmental aphasia and to normal children. The duration of a single tone varied from 75 msec to 250 msec and the intertone interval varied from 8 msec to 428 msec. They reported performance deficits in the aphasic children in the following conditions: when the tone duration was equal to 75 msec or 125 msec and the intertone interval was less than or equal to 150 msec; when the tone duration was equal to 175 msec and the intertone interval was less than or equal to 15 msec. There were no deficits observed for tone durations of 250 msec at any value of intertone interval, and no deficits for two-tone patterns when each tone was 75 msec at an intertone interval of 428 msec. The authors concluded that the total duration of the pattern was the critical variable associated with impaired performance. When the duration was below a value approximating 190 msec to 275 msec an impairment resulted. Above that duration, the aphasic children showed discrimination comparable to the normal children. These authors have also presented vowel sequences to dysphasic children (Tallal & Piercey, 1975). They found impairment for sequences of three to five sounds in the dysphasics when the vowels were 250 msec. Although a vowel of 250 msec could be accurately identified when presented in isolation, when presented in a sequence this ability was impaired. This result suggests that sequences are necessarily discriminated on the basis of a larger

time-unit than is required for the discrimination of single durations.

General Conclusions

The results of the present investigation are consistent with those of previous studies indicating that the left hemisphere is superior to the right in tasks which require the analysis of temporal information. However, the present findings suggest a limitation on the generality of this conclusion. It appears that a superiority in temporal processing may be demonstrated for the left hemisphere only if the stimulus durations employed do not exceed a critical value. Furthermore, the value of this critical duration, as determined in the present study, approximates the duration of cues underlying phonemic distinctions. Hence, the results of the present investigation lend substance to the notion that the left hemisphere's specialization for processing speech may be related to its specialization for temporal analysis. Specifically, it is suggested that tasks requiring the perception of speech qua speech and tasks requiring the perception of nonverbal temporal stimuli, as in the present study, are both dependent upon a specialized timing mechanism located in the left hemisphere. This conclusion identifies the temporal characteristics of verbal stimuli as at least one critical feature for their lateralization in the left hemisphere.

It has been suggested that the left hemisphere is

specialized for phonological, as opposed to auditory, analysis of stimuli (Studdert-Kennedy & Shankweiler, 1970). Phonological analysis is a term used to describe "the existence of a single phonetic feature processor (or extractor), in the dominant hemisphere whose output, the features, are the input to the linguistic system" (Godfrey, 1974, p.332). Thus, the superior identification of consonant phonemes in the left hemisphere is interpreted as a result of phonological analysis. On the basis of the present findings, it is suggested that phonological analysis is, in large part, synonymous with temporal analysis and that, temporal or phonological analysis provides the basis for overall linguistic analysis. That is, to describe a task as necessitating a phonological analysis implies that the task demands stimuli to be analyzed with respect to their temporal properties. This conclusion, in addition, does not identify the phonological-auditory distinction as fundamental in describing the selectivity of the left hemisphere for speech analysis.

The present findings led to the tentative suggestion that syllables and nonverbal stimulus sequences may also be processed in the left hemisphere provided that the task requires a temporal analysis. However, other modes of perceptual analysis are possible for these stimuli. It has previously been suggested that recognition of syllables or tonal sequences may be based on identification of these stimuli as integrated wholes (Bever & Chiarello,

1974; Levy, 1974; Papçun et al, 1974). Perception of a stimulus pattern as an integrated whole or gestalt, would not by definition involve a temporal analysis of that pattern. It therefore would not, according to the present account, depend upon a left-hemisphere timing mechanism. If, then, the task requires or the stimulus supports perception of syllables or nonverbal stimulus sequences as gestalt wholes, no left-hemisphere superiority would be expected. However, if the task requires that temporal features of these stimuli be processed, then a left-hemisphere advantage would be expected. Thus, extension of the present findings to the perception of syllables and stimulus sequences is clearly speculative. More data are required than are currently available in order to further an understanding of the processes underlying the lateralization of sequential stimuli and syllables.

Given these considerations, the type of timing mechanism located in the left hemisphere can, at the present time, be conceptualized as necessarily involved in analysis of stimulus durations of the order of magnitude of phonemic durations. The generality of this process to visually presented phonetic stimuli remains to be determined.

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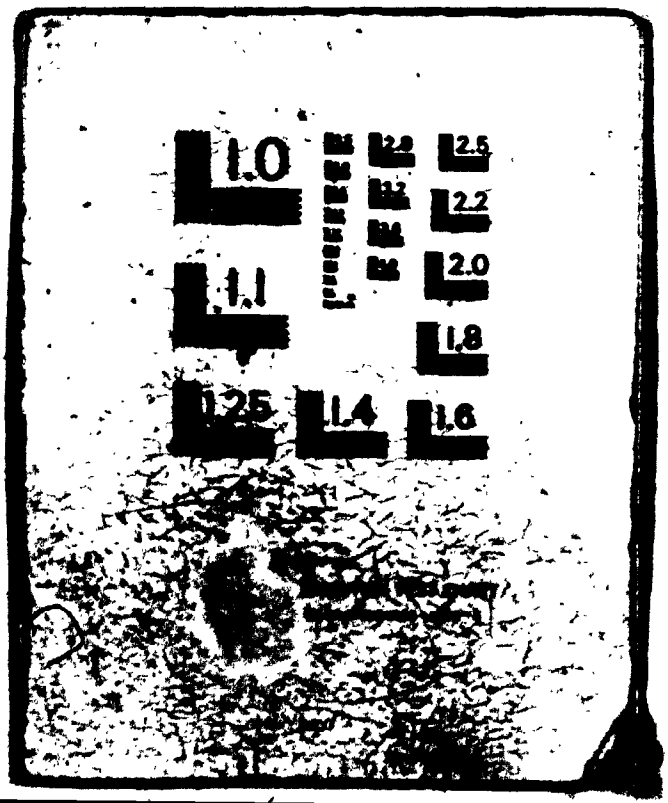

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TABLE 1

Mean threshold values in msec of individual subjects for right-first and left-first conditions of stimulation.

	Condition	
Subject	Left-first	Right-first
1	16	14
2	83	74
3	65	61
4	73	57
5	63	56
6	54	48
7	59	57
8	39	35
9	72	70
10	82	77

TABLE 2

Mean interval in msec at which two clicks are judged "simultaneous" for right-first and left-first conditions of stimulation, for each trial combined over subjects.

	Runs					
	Individual Means					Combined Mean
Left-first	62.5	60.5	61.5	56.5	62.0	60.6 sd=19.42
Right-first	52.0	58.0	58.0	52.5	54.0	54.9 sd=18.01

TABLE 3

(a) Mean reaction time in msec for left and right ear at each of four presentation rates.

Rate	Left Ear	Right Ear	p
10 per second	335.5	338.0	ns
15 per second	290.5	291.6	ns
20 per second	268.0	261.8	.01
25 per second	273.8	265.4	.01

(b) Mean reaction time in msec for left and right hands at each of four presentation rates.

Rate	Left Hand	Right Hand	p
10 per second	339.2	334.3	.01
15 per second	292.9	288.5	.01
20 per second	268.9	260.9	.01
25 per second	273.2	265.9	.01

TABLE 4

Difference thresholds in msec for indivudal and combined subjects longer judgments for the left and right ear and for intersequence interval, as estimated from probit analysis.

Subject	ISI	Left Ear	Right Ear
RO	5 sec	36.4	33.2
	2.5 sec	20.3	19.4
GB	5 sec	13.0	13.8
	2.5 sec	15.9	14.8
BB	5 sec	14.2	32.6
	2.5 sec	12.6	11.2
BA	5 sec	25.1	35.3
	2.5 sec	14.2	24.5
Combined	5 sec	18.9	25.7
	2.5 sec	15.4	16.3

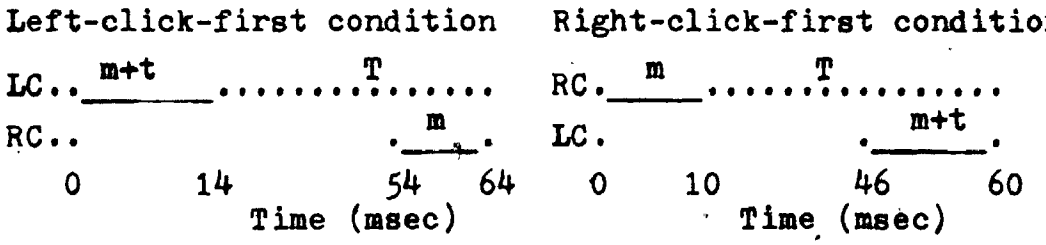
APPENDIX A

Schematic representation of rationale for hypothesis presented in Experiment I

1. It is assumed that the determination of successive order occurs within the left hemisphere. The threshold of successive order will then depend upon the arrival of the left-ear and the right-ear click within a given time period.

2. A click presented to the left ear will be transmitted to the right hemisphere and then information concerning its time of occurrence will be transferred to the left hemisphere. A click presented to the right ear will be transmitted directly to the left hemisphere. The internal timing process will commence upon arrival of the first click at the left hemisphere.

3. To illustrate the derivation of thresholds, a numerical example is as follows: Assume ear-hemisphere transmission time (m) = 10 msec; interhemispheric transmission time (t) = 4 msec; and the left-hemisphere threshold of successive order (T) = 50 msec.



Obtained threshold
= m + t + T - m
= 10+4+50-10
= 54 msec

Obtained threshold
= m + T -(m + t)
= 10+50 - 14
= 46 msec.

4. The difference in obtained thresholds , or LC - RC,

=m + t + T - m -(m + T -(m + t))
= 2t

Therefore, the obtained difference is equal to twice the interhemispheric transfer time.

APPENDIX B

Handedness Questionnaire

	Hand Preference		
	Left	Right	Both
Brush teeth			
Hammer a nail			
Throw a ball			
Strike a match			
Swing a raquet			
Write name			

APPENDIX C

Schematic representation of rationale for hypothesis presented in Experiment II.

1. Subjects response to sequence offset initiated when last click arrives in left hemisphere. Reaction time measure started at that time.

   Subjective time = time at which left hemisphere processing commences.

   Start - ST

   Stop - SP

2. C1 - first click; Cn - last click.

   I - interpulse interval within sequence

   t - hemisphere transfer time

   RT_T - total reaction time

   RT_M - reaction time for motor response

   X - transmission time to left or right hemisphere.

3. Left ear stimulation

   Clock .....
   C1 Cn

   Subjective time

   Cn
   .....
   ST X t I RT_M

   Therefore,

   RT_T Left = $X+t+I+RT_M$

   Right ear stimulation

   Clock .....
   C1 Cn

   Subjective time

   Cn
   .....
   ST X I RT_M

   therefore,

   RT_T Right = $X+I+RT_M$

4. $RT_{Left} - RT_{Right} = (X+t+I+RT_M) - (X+I+RT_M)$

   $= t.$

APPENDIX D

Experiment II: Analysis of Variance for Reaction Time Scores to the Offset of Pulse Sequences

Source	Ss	df	MS	F
Total	113149.74	55		
Between Ss	52396.34	6		
Within Ss	60753.41	49		
Ear	105.05	1	105.05	2.930
Error (ear)	215.13	6	35.85	
Rate	45220.93	3	15073.64	18.690**
Error (rate)	14517.29	18	806.52	
Ear x Rate	301.07	3	100.36	4.586*
Error (ear x rate)	393.93	18	21.89	

*$p < .05$

**$p < .01$

APPENDIX E

Experiment III: Analysis of Variance for Scores in the Perception of Stimulus Duration in a Dichotic Task

Source	Ss	df	MS	F
Total	175621.87	31		
Between Ss	42784.37	3		
Within Ss	132837.50	28		
Ear	8778.12	1	8778.12	2.948
Error (ear)	8934.37	3	2978.12	
Comparison Dur.	14878.12	1	14878.12	6.127
Error (comp.)	7284.37	3	2428.12	
ISI	12403.12	1	12403.12	2.089
Error (IXI)	17809.37	3	5936.46	
Ear x Comp.	14878.12	1	14878.12	5.052
Error (E x CD)	8834.37	3	2944.79	
Ear x ISI	2278.12	1	2278.12	1.161
Error (E x ISI)	5884.37	3	1961.46	
Comp. x ISI	25878.12	1	25878.12	25.585*
Error (CD x ISI)	3034.37	3	1011.46	
Ear x CD x ISI	153.12	1	153.12	.254
Error (E x CD x ISI)	1809.37	3	603.12	

*p < .01

APPENDIX F

Experiment IV: Analysis of Variance for Correct Scores in the Monaural Perception of Duration

Source	Ss	df	MS	F
Total	1400.24	99		
Within Ss	34.09	9		
Ear	25.00	1	25.00	12.5**
Error (ear)	18.00	9	2.00	
Duration	937.94	4	234.48	33.46***
Error(Dur)	252.60	36	7.01	
Ear x Duration	26.50	4	6.62	2.239
Error (ear x dur)	106.50	36	2.96	

**$p < .01$

***$p < .001$

APPENDIX G

Right hemisphere involvement in temporal tasks?

On the basis of the present results it has been argued that the left hemisphere is specialized for, and plays a primary role in, processing information relative to stimulus duration when those durations do not exceed a critical value. The results of Experiment II provided an estimate of this critical duration of approximately 50 msec. Such an argument implies that when stimulus durations or differences in duration do not exceed approximately 50 msec, the participation of the right hemisphere is, at best, minimal. However, several reports have appeared in the literature which may indicate a greater role for the right hemisphere in discriminating durations, than has herein been described. Murphy and Venables (1970b) presented subjects with paired clicks monaurally to the left or the right ear against a background of contralaterally presented white noise. The paired clicks were separated by 0 msec (i.e. simultaneous) or 10 msec. Subjects were requested to release one microswitch if two clicks were heard or a second microswitch if only one click was heard. Left-ear reaction times were significantly lower than right-ear reaction times in both simultaneous and successive presentation conditions. In a related study, Murphy and Venables (1970a) presented paired clicks separated by 0.1 msec or 2.0 msec to the subjects' left or right ears. Subjects were simply requested to respond whenever they

detected clicks separated by 2.0 msec. As in the earlier study, Murphy and Venables (1970b) found a significant left-ear advantage.

While the Murphy and Venables (1970 a,b) data appear to suggest right-hemispheric specialization in discriminating interclick intervals as small as 2 or 10 msec, the temporal acuity data discussed previously suggests a more probable interpretation of these findings. Experiments reported by Babkoff and Sutton (1963), Efron (1963) and Patterson and Green (1970) have demonstrated that while stimuli separated by intervals of 10 msec or less may be discriminated from simultaneously presented stimuli, the basis for the discrimination appears to be loudness or pitch cues rather than temporal cues per se. In fact, Murphy and Venable's (1970 a,b) subjects reported using pitch cues to facilitate their performance. Accordingly, the Murphy and Venables (1970 a,b) studies might be interpreted as examples of right-hemisphere involvement in tasks which were not essentially temporal.

Milner (1962) and Spellacy (1970) have reported data indicating that in certain tasks the right hemisphere may process temporal information as well as or better than the left hemisphere. Milner (1962) administered the Seashore Measures of Musical Talents to a group of right-hemisphere and a group of left-hemisphere epileptics, both before and after surgery. Two of the subtests, "Time" and "Rhythm" are of particular interest. On the Rhythm subtest, two rhythmic tonal patterns are presented and subjects are required to judge whether the

rhythm of the patterns is the same or different. On the Time subtest, subjects are presented with two tones, differing in duration by 50 to 300 msec, and are requested to indicate whether the second tone is longer or shorter than the first. Milner's (1962) results indicated that the error scores of both right-hemisphere damaged and left-hemisphere damaged patients increased on the subtests following surgery. While the right-hemisphere group showed a greater increase in errors than the left-hemisphere group on both tests, this was statistically significant only for the Time subtest. Although Milner did not include data which might assist in interpreting these results (e.g. pattern of error scores, duration discrimination thresholds) her report clearly suggests greater right than left-hemisphere participation in the temporal tasks employed. These results are puzzling since they are contrary to several other clinical studies of duration discrimination, comparable to the Time subtest (Gordon, 1967; Needham & Black, 1970; Van Allen et al., 1966).

Spellacy (1970), employing a dichotic stimulation procedure, presented subjects with pairs of temporally patterned stimuli. Each pattern consisted of tone pulses of 100, 200, 300 or 400 msec duration, individual pulses being separated by 200, 300 or 400 msec. The total duration of each pattern was 2 sec. The termination of each dichotically presented pair initiated a retention interval of 5 or 12 sec following which subjects heard a single tonal pattern and were requested to judge whether or not it had been a member of the preceding dichotic pair. The results indicated no significant ear

difference at the 5 sec retention interval. Although a trend favoring the right ear appeared at the 12 sec retention interval, it was not statistically significant.

As noted previously, the Milner (1962) and Spellacy (1970) results are not readily assimilated to an hypothesis which maintains that the right hemisphere is minimally involved in temporal tasks. It is apparent that the right hemisphere does participate and may be superior to the left in certain temporal discrimination tasks. Further research is required to clarify the nature of those temporal tasks in which right-hemisphere processes are involved.